AJEEE

ISSN: 2582-0257

ADBU Journal of
Electrical and Electronics Engineering

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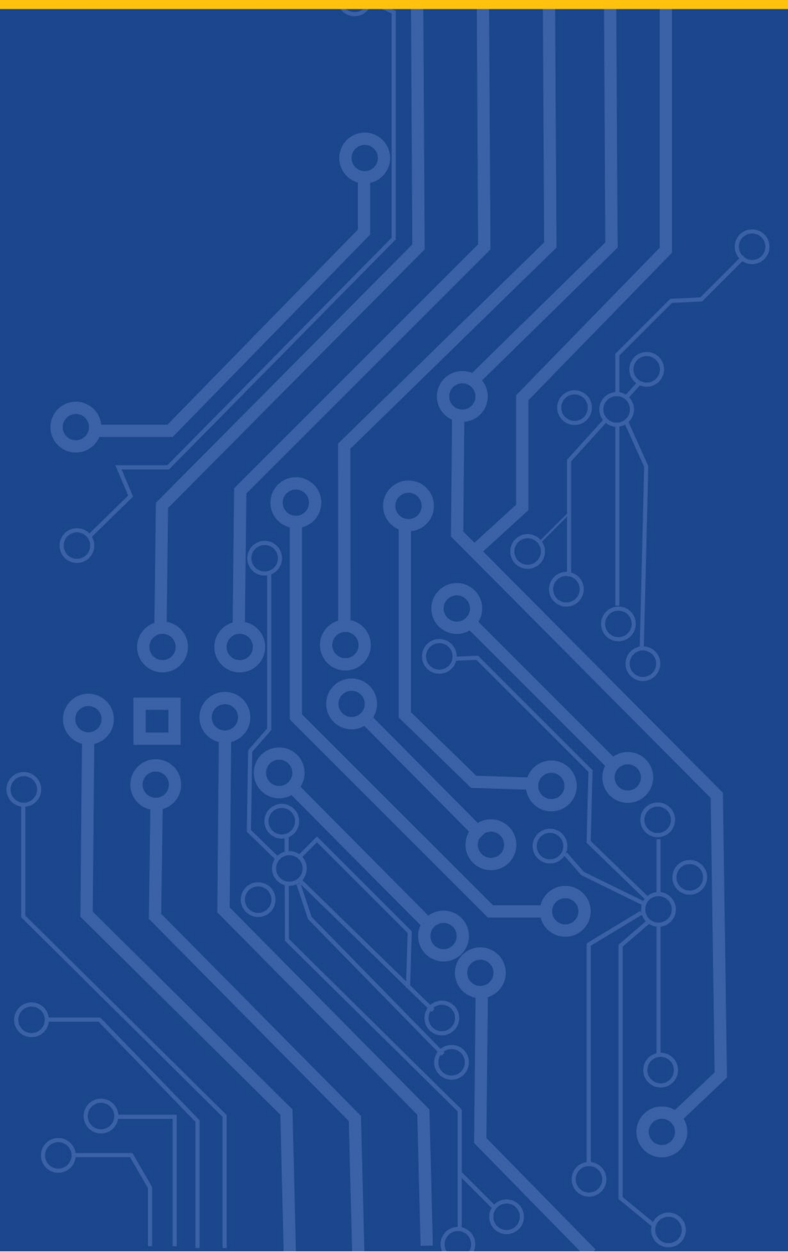
Volume 1 Issue 1



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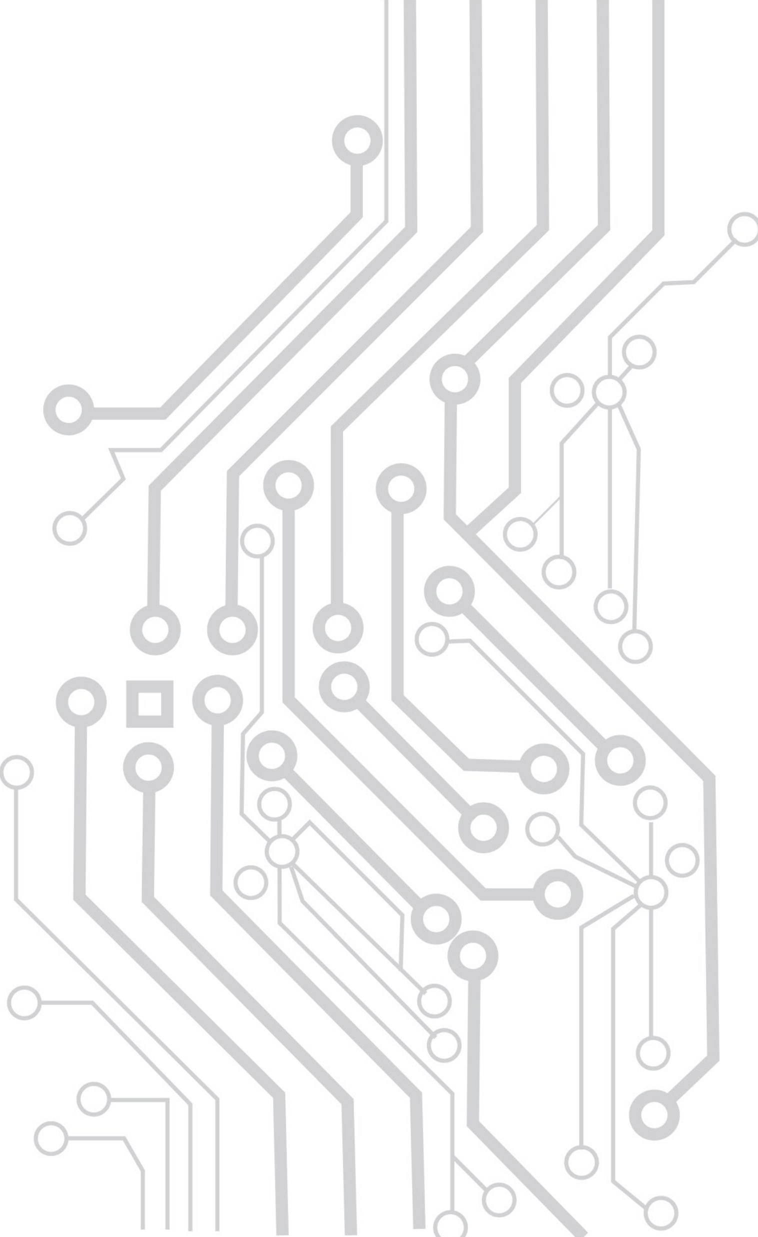

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ADBU Journal of Electrical and Electronics Engineering (AJEEE)

ISSN: 2582-0257

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Website: www.tinyurl.com/ajeee-adbu , http://journals.dbuniversity.ac.in/ojs/index.php/AJEEE

Volume 1, Issue 1

Published in May, 2017

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Contents

Bluetooth Controlled Metal Detector Robot

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Abstract: ***This paper presents a new type of robot that uses a metal detector sensor to detect metallic object passing over the metal detector. The robotic vehicle is controlled using android application for metal detection operation controlled with the help of Bluetooth technology. This project can be widely used because of its simplicity and ability to modify to meet changes of needs. Based on experimental studies, it was found that the mobile controlled robot can move in any direction as per the desired instruction and the beeper in the metal detector circuit beeps whenever it encounters any metallic object.***

Keywords: Arduino UNO, Bluetooth Module HC-05, Metal Detector, Motor Driver, Android Application

1. Introduction

In today’s modern environment, almost everybody uses smartphones, which are a part of their day-to-day life. This project was about robotic movement control through smartphones. Many researchers [1] have developed such robotic movement control system using smartphones. Here, we aim to make a robot and to connect the metal detector circuit to it.

Here, a dedicated application has been created to control robotic hardware, which controls the movement of the robot. The embedded hardware has been developed on ATmega328P microcontroller and controlled by an Android smartphone. This controller receives the commands from the Android phone, takes the data and controls the motors of the robot by the motor driver L293D. The robot can able to move forward, backward, left and right movements. The Smartphone is been interfaced to the device by using Bluetooth. A Bluetooth device HC-05 module was used with Arduino UNO to receive commands from the smartphone. A metal detector circuit was connected to the robot to detect the metal. A beep sound was made when it detected the metal.

2. Methodology

This work is divided into two sections- hardware and software. Hardware section contains robot making, metal detector, and control unit. In the hardware section, we explain the working of Arduino and DC motors and how the robot utilizes them to detect the metallic obstacles. In the section of the metal detector, we describe general information about kind of metal detector and working principles. In the section of the control unit, we describe what kind of microcontroller we use. While in the software section, we explain the algorithm that we use in making the android application and metal detector.

A simple block diagram is shown in Figure 1 below.

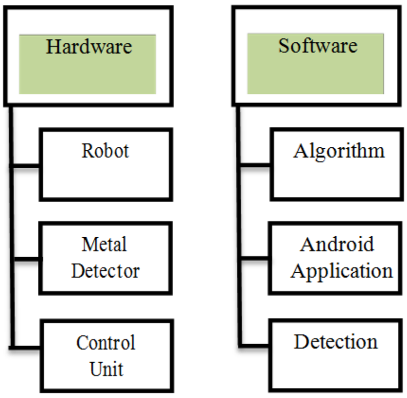


Figure 1: Working Sections in this work

3. Hardware Design

Hardware design consists of the Bluetooth controlled robot and the metal detector circuit. In this work, we utilized the components to build a configurability robot to reach our goal.

The circuit for Bluetooth controlled metal detector robotic car is shown in Figure 2. The Motor driver is connected to Arduino to run the car. Motor driver’s input pins 2,7,10 and 15, are connected to Arduino digital pin numbers 12, 11, 10 and 9 respectively. Here we have used two DC motors to drive a car in which one motor is connected at the output pin of motor driver-3 and 6; and another motor is connected to pins- 11

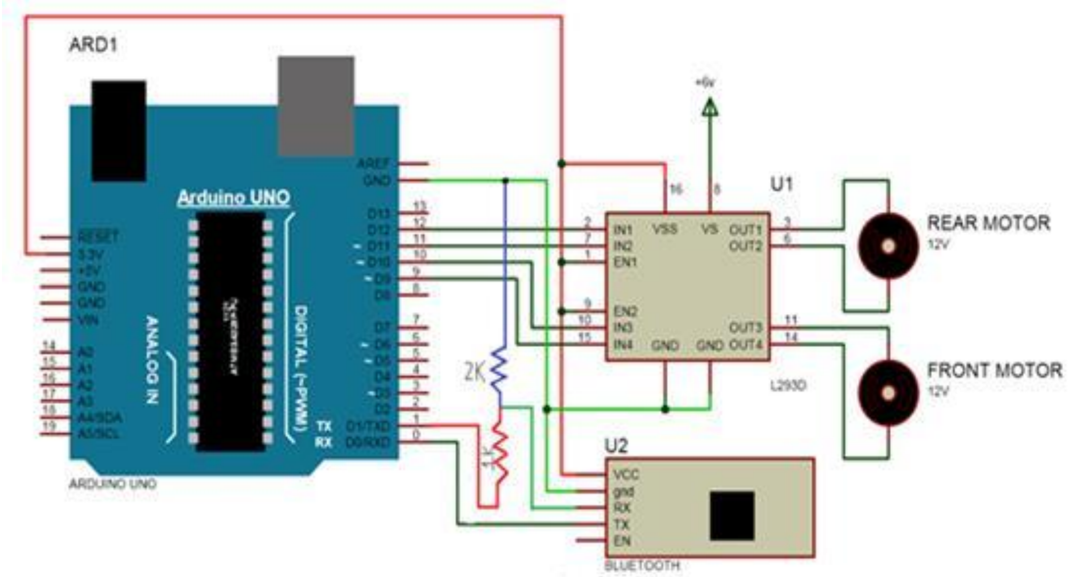


Figure 2: Robotic Vehicle Circuit using Arduino UNO

and 14. A 9V battery is also used to power the motor driver for driving motors. The Rx pin of the Bluetooth module is connected to a voltage divider. From the voltage divider, one end is connected to the Tx pin of the Arduino and the other end is connected to the ground (GND) pin of the Arduino. Then the Tx pin of the module is connected to the Rx pin of the Arduino.

3.1 Robotic vehicle circuit

The robotic vehicle consists of Arduino UNO, Bluetooth Module HC-05, Metal Detector, Motor Driver and two DC Motors. The Vcc and ground pin of Bluetooth module is connected to 3.3V and ground of Arduino. A 9V battery is also used for power the circuit at Arduino V_{in} pin.

3.1 Metal detector

In this work, we mainly depend on a metal detector, because we need to decide the object is metallic or non-metallic. A metal detector device detects the presence of metal nearby. It takes advantage of the electric and magnetic properties of metals (Eddy currents) to detect metals [2].

The circuit for the metal detector circuit is shown in Figure 3, whose working is as follows.

Here the circuit is divided into three parts, an astable multivibrator, an LC circuit, and a comparator circuit. In the first stage i.e., the astable multivibrator circuit (using NE 555 IC), by giving a supply to the circuit it produces a frequency (say f_1) and this frequency is fixed by adjusting the variable resistor R1 and R2 which are of the value 2K and 25K respectively. It produces a square wave at the output pin (i.e. pin 3) of the IC and is adjusted to give a frequency of 0.7 MHz.

In the second stage is the LC circuit. The inductance (L) here is a copper coil. When a metal is kept near to the coil, the electromagnetic field in the coil is disturbed which produces a frequency (say f_2). The frequencies f_1 and f_2 meet at a junction. If frequency f_1 is greater or lesser then f_2, it produces a voltage V, the voltage flows through the diodes. The negative voltage flows through diode D1, which is in reverse bias that is connected to the ground and it gets neutralize here. Whereas, the positive voltage flows through diode D2 which is in forward bias. The capacitor C5 reduces the

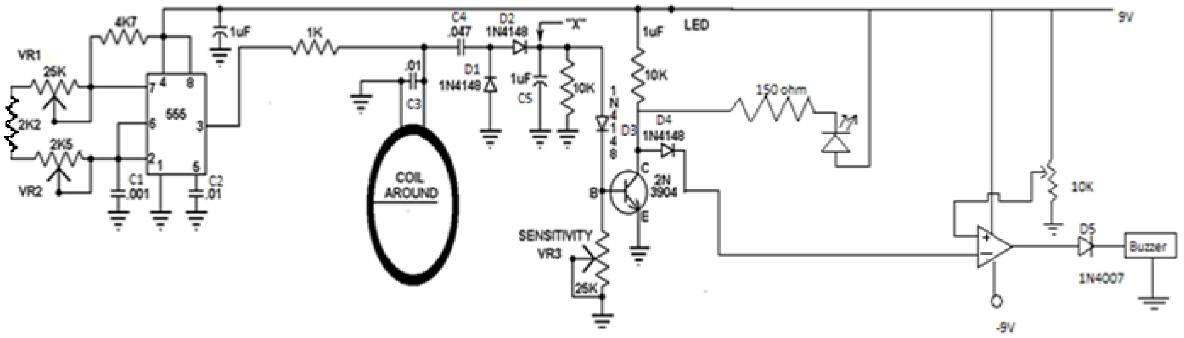


Figure 3: Robotic Vehicle Circuit using Arduino UNO

ripples in the voltage. Whenever the voltage flows through diode D3, if there is any negative voltage, it will be blocked by the diode and only positive voltage is allowed to pass which then flows to the NPN transistor. The transistor will be switched ON and a positive voltage will flow through diode D4; and then a positive voltage will flow to the pin 2 of the op-amp in the comparator circuit, which is in inverting mode. Here a variable resistor is connected to pin 3 of the op-amp, which sets the reference voltage of the comparator circuit. Here the voltage at pin 2 will be lower than the reference voltage at pin 3, so the output at pin 6 (output pin) will be high and a voltage from the op-amp will flow to diode D5 and then to the buzzer and the buzzer will beep.

However, when there is no metal near the coil, frequency f_1 will be equal to f_2, the voltage produced at the junction will be zero, and hence there will be no voltage flowing across the circuit. The input at pin 2 will be more than the reference voltage, so the output will be low, therefore the buzzer will not beep.

3.3 Control Units (Arduino UNO, ATmega328P Microcontroller)

The Arduino Uno is the main hardware control unit, which is a microcontroller board and is based on the ATmega328P. It has 14 digital input/output pins, 6 analog inputs, a 16 MHz quartz crystal, a USB connection, a power jack, an ICSP header and a reset button [3]. It contains everything that is needed to support the microcontroller; simply it needs to be connected to a computer with a USB cable or power it with an AC-to-DC adapter or battery, to get started.

4. Software Design

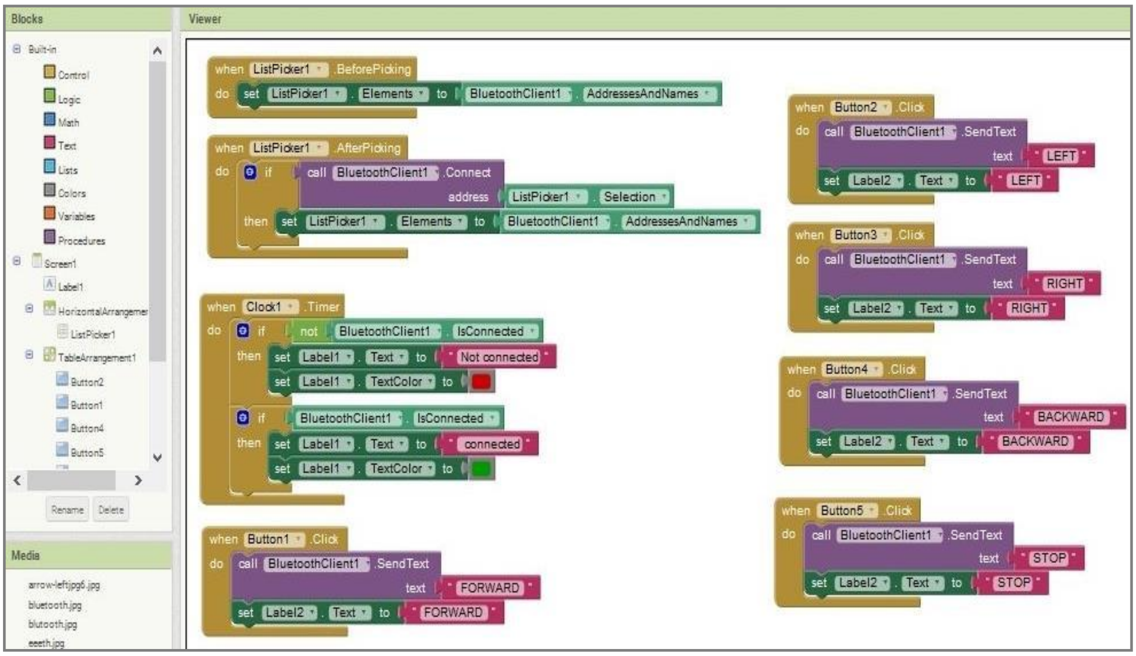
In this section, algorithms used in making the android application and metal detection, have been briefly explained. Here, we utilized the advantages of an Android smartphone. The software components have been described with more details.

4.1 Algorithm

The general algorithm has the main steps to accomplish the general tasks, which are “start”, “stop” and “detection of metal”. The program will begin with the “start” step where the Bluetooth module HC-05 connected to Arduino Uno will pair with the android application. The robot moves as per the instruction, given by the Android Application. During this step, the robot moves and the metal detector checks if the object is a metallic object or not through passing it over the metal detector. In case, if a metallic object is countered by the metal detector, a beep sound will be produced by the beeper and the movement of the robot can be stopped. Otherwise, the robot will travel until it finds any metallic object, or else the movement robot can be stopped.

4.2 Android Application

Android is a very familiar word in today’s world. Millions of devices are running on Android OS and millions are being developed every day [4]. **App Inventor** is an application originally provided by Google and now maintained by the Massachusetts Institute of Technology (MIT). It allows anyone to create software applications for the Android Operating System (OS). It uses a graphical interface that allows users to create an application



```
when ListPicker1 .BeforePicking
do  set ListPicker1 . Elements to  BluetoothClient1 . AddressesAndNames

when ListPicker1 .AfterPicking
do  if   call BluetoothClient1 .Connect
                               address  ListPicker1 . Selection
    then  set ListPicker1 . Elements to  BluetoothClient1 . AddressesAndNames

when Clock1 .Timer
do  if   not  BluetoothClient1 . IsConnected
    then  set Label1 . Text to  " Not connected "
          set Label1 . TextColor to 🟥
    if   BluetoothClient1 . IsConnected
    then  set Label1 . Text to  " connected "
          set Label1 . TextColor to 🟩

when Button1 .Click
do  call BluetoothClient1 .SendText
                          text  " FORWARD "
    set Label2 . Text to  " FORWARD "

when Button2 .Click
do  call BluetoothClient1 .SendText
                          text  " LEFT "
    set Label2 . Text to  " LEFT "

when Button3 .Click
do  call BluetoothClient1 .SendText
                          text  " RIGHT "
    set Label2 . Text to  " RIGHT "

when Button4 .Click
do  call BluetoothClient1 .SendText
                          text  " BACKWARD "
    set Label2 . Text to  " BACKWARD "

when Button5 .Click
do  call BluetoothClient1 .SendText
                          text  " STOP "
    set Label2 . Text to  " STOP "
```

Figure 4: App Inventor Designer

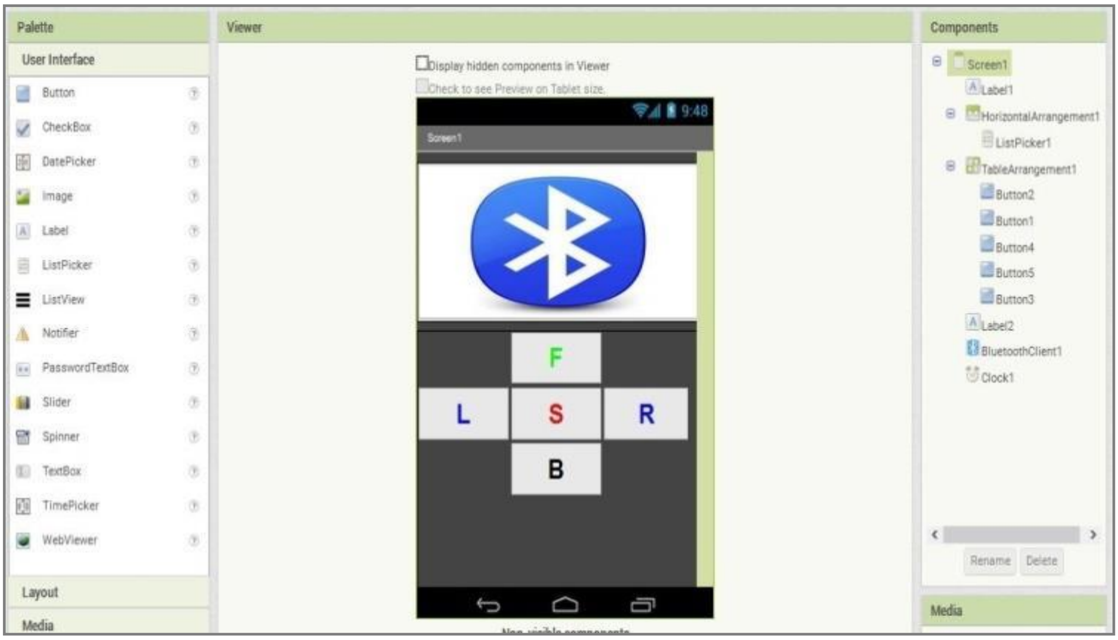


Figure 5: Apps Inventor Block Editor

that can run on the Android system, which runs on many Android phones [5].

The first phase of application design goes through the **App Inventor Designer**, which is accessible through the web page. The left side of the window consists of ingredients like a screen, buttons, text boxes, images, labels and many more and the right side of the designer allows users to view the screen and components added to the screen.

In this app development, the **App Inventor** provides a versatile opportunity to develop a customized application that starts with establishing a Bluetooth connection by searching the available Bluetooth devices and make pair with them. For robotic movement, a character is assigned for each operation such as Forward-“F”, Backward-“B”, Left-“L” and Right-“R”.

4.3 Detection

This task completely depends on the metal detector. Whenever the metal detector comes across and metal, it detects the metal by making a beep sound.

5. Operation of the System

The project is designed to control a metal detector robotic vehicle using an android application. Bluetooth device is interfaced to the control unit for sensing the signals that are transmitted by the android application. This data is conveyed to the control unit, which moves the robot. An ATmega328P microcontroller is used in this project as a control device.

Remote operation is achieved by any smartphone with Android OS, upon a GUI (Graphical User Interface) based touch screen operation. We used the HC-05 module to pair the Android application to the robot. The motors are interfaced to the control unit through motor driver L293D IC. An extra metal detector circuit is connected to the robot to detect the metal efficiently.

6. Conclusion and future scope

This project presents a metal detecting robot using Bluetooth communication with Bluetooth module HC-05. The robot is moved in a particular direction with the help of Bluetooth technology, controlled by our mobile. Experimental work has been carried out successfully. The result shows that higher efficiency is achieved using the embedded system. This proposed method is verified to be highly beneficial for many purposes [6]. The metal detector worked at a constant speed without any problem. In this project, we also achieved wireless communication between the robot and the Android application.

This project can be further developed by enhancing the performance and by adding more features. Further developments in this project can be an addition of features like the addition of a gas sensor, connecting robotic arms for pick and place purposes etc.

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ADBU Journal of Electrical and Electronics Engineering (AJEEE) | Volume 1, Issue 1 | May 2017

A Review on Sliding Mode Control: An Approach for Robust Control Process

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Abstract: ***The main objective of this paper is to review various research works related to the modelling of Sliding Mode Controller (SMC) for process control carried out by different researchers for designing high-performance nonlinear controller in the presence of uncertainties. The effects of the controller over non-linear process have made it the most adaptive type to any uncertainties in it. Although it has its own problem, referred to as the chattering phenomenon, there are the methods as discussed in this paper to eliminate it.***

Keywords: Sliding Mode Control (SMC), process control, Variable Structure Control (VSC), Robust control, Non-linear process, Chattering phenomena, Lyapunov stability

1. Introduction

A very small change in a process can have a large impact on the end result. The change in proportions, temperature, flow, tolerance, and many other factors must be carefully and persistently controlled to yield the desired end product with a very limit of raw materials and energy. Process control technology enables manufacturers to keep their operations running with specified limits and set more precise limits to maximize profitably, ensure quality and safety. The Process industries include the chemical industry, the oil and gas industry, the food and beverage industry, the water treatment and the power industry.

Process control can lower variability in the end product, thereby ensuring a consistently high-quality product. A process variable is a condition of the process fluid that can change the manufacturing process in some way. The controller is a device that receives data from a measurement instrument, compares the data to a programmed set-point, and, if necessary, signals a control element to take corrective action [20].

SMC is an important robust control approach. The class of systems for which it applies, SMC design provides a systematic approach to the problem of maintaining accuracy, robustness, stability, easy tuning, and consistent performance in the face of modelling imprecision [1]. There are two major advantages of sliding mode control. First, the dynamic behaviour of the system may be tailored by the particular choice of a sliding function. Secondly, the closed loop response becomes totally unresponsive to some particular uncertainties. Due to this property, this principle extends to model parameter uncertainties, also any disturbances and non-linearity that are bounded in the systems. From a practical point of view, an SMC enables controlling of nonlinear processes subjected to the external disturbances and heavy model uncertainties.

There are some modelling inaccuracies that can occur in these controllers. It can be classified into two major kinds- structured (or parametric) uncertainties and unstructured uncertainties (or un-modelled dynamics). The former kind corresponds to inaccuracies on the terms actually included in the model, while the later kind deals with the inaccuracies on the system order. One of the important approaches to deal with model uncertainty is robust control [1].

2. Theoretical Background

The SMC is a two-part controller design. The first part associates with the design of a sliding surface so that the sliding motion satisfies the design specifications dealt with it. The second focuses on the selection of a control law that will make the switching surface attractive to the system state [3].

One job is to investigate the variable structure control (VSC) as a high-speed switched feedback control, resulting in the sliding mode. The aim of the switching control law is to drive the nonlinear plant's state trajectory onto a pre-specified (user-chosen) surface in the state space and to maintain the plant’s state trajectory on this surface for a subsequent time, the surface being termed a switching surface. When the plant’s state trajectory is “above” the surface, the feedback path has some gain, which is different if the trajectory drops “below” the surface. This surface helps us to define the rule for proper switching. This surface is also called a sliding manifold. Ideally, once intercepted, the switched control retains the plant’s state trajectory on the surface for all the successive time and the plant’s state trajectory slides along this surface. The most crucial task is to develop a switched control that will drive the plant state to the switching surface and maintain it on the surface upon interception [1].

If we can control and restrict the dynamics of the system to lie on a well-behaved surface, then the control problem is greatly simplified. It is defined in such a way that the error dynamics are exponentially stable when the system is restricted to lie on this surface. The control problem, which minimizes the problem of driving the system to this surface, and then ensuring that it stays on this surface all the time [2], a Lyapunov approach is used to characterize this task. The Lyapunov method is usually used to determine the stability properties of an equilibrium point without solving the state equation. Let $V(x)$ is a continuously differentiable scalar function defined in a domain D that contains the origin. A function $V(x)$ is said to be positive definite if $V(0) = 0$ and $V(x) > 0$ for x. It is said to be negative definite if $V(0) = 0$ and $V(x) >$ 0 for x. The Lyapunov method is to assure that the function is positive definite when it is negative and function is negative definite when it is positive. In that way, the stability is assured. For each chosen switched control structure, particular “gains” can be selected so that the derivative of this Lyapunov function is negative definite, thus assuring the motion of the state trajectory to the surface. After the proper design of the surface, a switched controller is developed with the tangent vectors of the state trajectory pointing towards the surface so that the state is driven to and maintained on the sliding surface. Such controllers introduces discontinuous closed-loop systems [1].

Let us consider a single input nonlinear system, defined as

$$x^{(n)} = f(x,t) + b(x,t)u(t) \qquad \text{........... (1)}$$

Here, $x(t)$ is a state vector, $u(t)$ is a control input and x is the output state of the interest [1]. The other states in the state vector are the higher order derivatives of x up to the $(n\text{-}1)^{th}$ order. The superscript n on $x(t)$ shows the order of differentiation. $f(x,t)$ and $b(x,t)$ are generally nonlinear functions of time and states. The function $f(x)$ is not exactly known, but the extent of the imprecision on $f(x)$ is upper bounded by a known, continuous function of x; similarly, the control gain $b(x)$ is not exactly known, but is of known sign and is bounded by known, continuous functions of x.

A time-varying surface $s(t)$ is defined in the state space by equating the variable $s(x,t)$, defined below, to zero.

$$s(x;t) = \left(\frac{d}{dt} + \delta\right)^{n-1} \tilde{x}(t) \qquad \text{.................. (2)}$$

Here, δ is a strict positive constant, taken to be the bandwidth of the system,

$\tilde{x}(t) = x(t) - x_d(t)$ is the error in the output state, where is the desired state.

The strategy to converge to the sliding mode is that we can add something to $u(t)$, which will drive us to the sliding mode in a finite time. In summary, the motion consists of a reaching phase during which trajectories starting off the manifold $s(t)$ move toward it and reaches it in finite time, followed by a sliding phase during which the motion is confined to the manifold $s(t)$ and the dynamics of the system are represented by the reduced-order model. The manifold $s(t)$ is called the sliding manifold and the control law $u(x)sgn(s)$ is called sliding control mode [2].

Moreover, bounds on ***s*** can be directly translated into bounds on the tracking error vector $\tilde{x}(t)$, and therefore the scalar ***s*** represents a true measure of tracking performance.

The corresponding transformations of performance measures assuming $\hat{x}(0) = 0$ is:

$$\forall t \geq 0, |s(t)| \leq \phi => \forall t \geq 0, \left|\hat{x}^{(i)}(t)\right| \leq (2\delta)^i \varepsilon, \quad i = 0,1,\ldots\ldots,n-1 \qquad \text{........................... (3)}$$

where $\varepsilon = \phi/\delta^{\,n\text{-}1}$

In this way, an n^{th} order tracking problem can be replaced by a first-order stabilization problem.

The simplified first-order problem of keeping the scalar ***s*** at zero, can now be achieved by choosing the control law ***u*** of Eqn. (1) such that outside of $s(t)$

$$\frac{1}{2}\frac{d}{dt}s^2 \leq -\eta|s| \qquad \text{....................... (4)}$$

Eqn . (4) states that the squared “distance” to the surface, as measured by $\boldsymbol{s}^2$, reduces along all system trajectories. Thus, it constraints trajectories to point towards the surface $s(t)$. In particular, once on the surface, the system trajectories are maintained on the surface. Strictly speaking, satisfying the sliding condition makes the surface an invariant set (a set for which any trajectory starting from an initial condition within the set, remains in the set for all future and past times). Furthermore, Eqn. (4) also denotes that some disturbances or dynamic uncertainties can be tolerated while still keeping the surface an invariant set.

Finally, satisfying Eqn. (2) guarantees that $x(t = 0)$ is actually off $x^d (t = 0)$, the surface $s(t)$ will be reached in a finite time smaller than $|s(t = 0)|/\eta$.

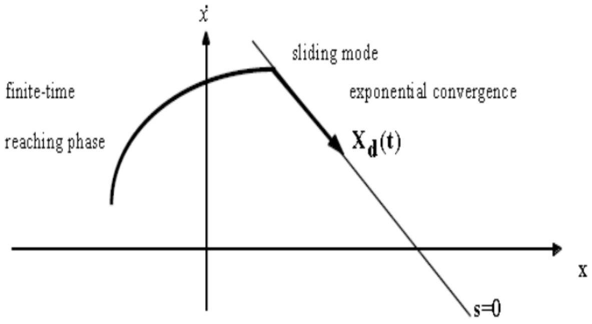


Figure 1: Graphical interpretation of Eqns. (2), (4) (for n = 2) [19]

3. Controller Design

The controller design procedure can be divided in two steps. In the first step, a feedback control law ***u*** is selected to verify the sliding condition in Eqn. (4). But, in order to account for the presence of modelling imprecision and of disturbances, the control law has to be discontinuous across $s(t)$. Since the implementation of the corresponding control switching is imperfect, this leads to chattering (Figure 2), which is undesirable in practice as it involves high control activity and may excite high-frequency dynamics neglected in the course of modelling [1]. Hence, in the second step, the discontinuous control law ***u*** is suitably smoothed to achieve an optimal trade-off between control bandwidth and tracking precision. The first step accomplishes robustness for parametric uncertainty; the second step achieves robustness to high-frequency unmodeled dynamics.

Consider a simple second order system,

$$\ddot{x}(t) = f(x,t) + u(t) \quad \text{........................ (5)}$$

where $f\,(x,t)$ is generally nonlinear and/or time-varying, and can be estimated as $\hat{f}(x,t)$; $u(t)$ is the control input; $x(t)$ is the state to be controlled such that it follows the desired trajectory $x_d\,(t)$ [1]. The estimation error on $f(x,t)$ can be assumed to be bounded by some known function $F = F(x,t)$, so that

$$\left|\hat{f}(x,t) - f(x,t)\right| \le F(x,t) \quad \text{.................. (6)}$$

We define a sliding variable according to Eqn. (2).

$$s(t) = \left(\frac{d}{dt} + \gamma\right)\tilde{x}(t) = \dot{\tilde{x}}(t) + \dot{\gamma}\hat{x}(t) \quad \text{............ (7)}$$

Differentiation of the sliding variable yields

$$\dot{s}(t) = \ddot{x}(t) - \ddot{x}_d(t) + \gamma\dot{\hat{x}}(t) \quad \text{....................... (8)}$$

Substituting Eqn. (5) in Eqn. (8), we have

$$\dot{s}(t) = f(x,t) + u(t) - \ddot{x}_d(t) + \gamma\dot{\tilde{x}}(t) \quad \text{............. (9)}$$

The approximation of control law $\hat{u}(t)$ to achieve $\dot{s}(t) = 0$ is:

$$\hat{u}(t) = -\hat{f}(x,t) + \ddot{x}_d(t) - \gamma\dot{\tilde{x}}(t) \quad \text{................ (10)}$$

$\hat{u}(t)$ can be thought of as the best estimate of the equivalent control.

To accommodate uncertainty in f while satisfying the condition

$$\frac{1}{2}\frac{d}{dt}(s(t)^2) \le -\eta|s(t)|, \quad \eta > 0 \quad \text{.................... (11)}$$

The control law can be taken as:

$$u(t) = \hat{u}(t) - k(x,t)\,sgn(s(t)) \quad \text{................... (12)}$$

By selecting $k(x,t)$ large enough, such as

$$k(x,t) = F(x,t) + \eta$$

ensures the satisfaction of condition in Eqn. (11), since

$$\frac{1}{2}\frac{d}{dt}(s(t)^2) = \dot{s}(t)s(t)$$
$$= \left(f(x,t) - \hat{f}(x,t)\right)s(t) - k(x,t)|s(t)| \le -\eta|s(t)|, \quad \eta > 0 \quad \text{.. (13)}$$

Hence, by using Eqn. (12), we ensure that the system trajectory will take a finite time to reach the surface $s(t)$, after which the errors will exponentially reduce to zero.

Now considering another second order system in the form of

$$\ddot{x}(t) = f(x,t) + b(x,t)u(t) \quad \text{.............................. (14)}$$

where $b(x,t)$ is bounded as

$$0 \le b_{min}(x,t) \le b(x,t) \le b_{max}(x,t)$$

The control gain $b(x,t)$ and it's bound can be time-varying or state dependent. Because the control input is multiplied by the control gain in the dynamics, the geometric mean of the lower and upper bound of the gain is an acceptable estimate:

$$\hat{b}(x,t) = \sqrt{b_{min}(x,t)b_{max}(x,t)}$$

Then, bounds can be written as

$$\beta^{-1} \le \frac{\hat{b}}{b} \le \beta \text{ where } \beta = (b_{max}/b_{min})^{1/2}$$

Since the control law will be designed to be robust to the bounded multiplicative uncertainty, β is called the gain margin of the design.

It can be proved that the control law

$$u(t) = \hat{b}(x,t)^{-1}[\hat{u}(t) - k(x,t)sgn(s(t))] \quad \text{..... (15)}$$

with

$$k(x,t) \ge \beta(x,t)(F(x,t) + \eta) + (\beta(x,t) - 1)|\hat{u}(t)| \quad \text{.......... (16)}$$

satisfies the sliding condition.

4. Chattering Reduction

An ideal sliding mode occurs only when the state trajectory *x*(*t*) of the controlled plant agrees with the desired trajectory at every $t \leq t_1$ for some t_1 . This may require infinitely fast switching. In real systems, a switched controller has inadequacy which limits switching to a finite frequency. The representative point then oscillates within a neighbourhood of the switching surface. This oscillation, called chattering [1], is illustrated in Figure 2.

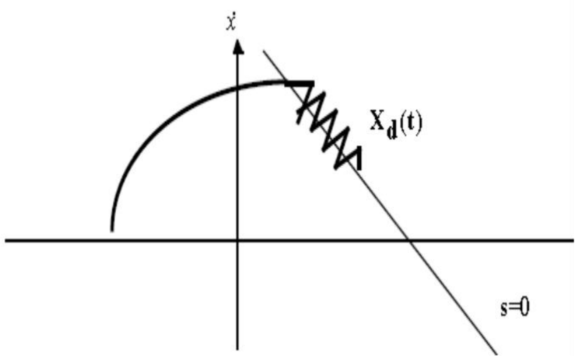
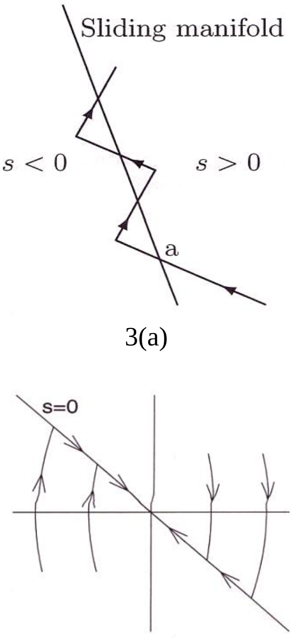


Figure 2: Chattering as a result of imperfect control switching [19]

We have to note that the controller is discontinuous at *s*(*t*). Due to the effects of sampling, switching and delays in the devices used to implement the controller, respectively in the simulation engines used when modelling the controlled system, sliding mode control suffers from chattering The next figure shows how delays can cause chattering. It depicts a trajectory in the region *s*(*t*) heading toward the sliding manifold *s*(*t*). It first hits the manifold at a point a. In ideal sliding mode control, the trajectory should start sliding on the manifold from a point a. In reality, there will be a delay between the time the sign of ***s*** changes and the time the control switches. During this delay period, the trajectory crosses the manifold into the region *s*(*t*) [2].

There are many strategies used to avoid chattering; e.g., you can introduce a boundary layer. Here, the ***sgn*** function is made continuous by using a piecewise linear approximation. Within the boundary layer, you have exponentially convergence to the sliding mode. You rely on continuity arguments to show that the system will still converge [2].

Chattering results in low control accuracy, high heat losses in electrical power circuits and high wear of moving mechanical parts. It may also excite unmodeled high-frequency dynamics, which degrades the performance of the system and may even lead to instability [2].



3(a)

3(b)

Figure 3: (a) When s < 0 and s > 0
(b) When s = 0 [2].

Control laws which satisfy the sliding condition in Eqn. (4) and lead to “perfect” tracking in the face of model uncertainty, are discontinuous across the surface *s*(*t*), thus causing control chattering. Chattering is undesirable as it involves extremely high control activity and besides, may excite high-frequency dynamics neglected in the course of modelling. Chattering must be reduced (or eliminated completely if possible) for the controller to perform properly. This can be achieved by smoothing out the control discontinuity in a thin boundary layer neighbouring the switching surface.

$$B(t) = \{x, |s(x;t)| \leq \phi\} \qquad \phi > 0$$

where ϕ is the boundary layer thickness, and
$\varepsilon = \phi / \lambda^{n-1}$ is the boundary layer width.

That means, outside of *B*(*t*), we choose control law as mentioned earlier, which assures that the boundary layer is attractive, hence invariant. All the trajectories starting inside *B*(*t* = 0) remain inside *B*(*t*) for all $t \geq 0$, and then *u* is interpolated inside *B*(*t*); e.g., *sgn*(*s*) in Eqn. (12) can be replaced by $\frac{s}{\phi}$ inside *B*(*t*).

5. Existing Case Studies

In a research done by Ruben Rojas, Oscar Camacho and Luis Gonzalez [4], a first order plus dead time model of the process for controlling open-loop unstable systems. The proposed controller has a simple and fixed structure with a set of tuning equations as a function of the desired performance. Both linear and non-linear models were used to study the controller performance by computer simulations.

In the research by Oscar Camacho and Carlos A. Smith [5], has shown the synthesis of a sliding mode controller based on a FOPDT model of the actual process. The controller obtained is of the fixed structure. A set of equations obtains the first estimates for the tuning parameters. The examples presented indicate that the SMC performance is stable and quite satisfactory in spite of non- linearity over a wide range of operating conditions.

In the research work by Chyi-Tsong Chen and Shih-Tien Peng [6], a novel and systematic sliding mode control system design methodology is proposed, which integrates an identified Second-Order Plus Dead-Time (SOPDT) model, an optimal sliding surface and a delay-ahead predictor. Besides, with the concept of delay equivalent, the proposed sliding mode control scheme can be utilized directly to the regulation control of a non-minimum phase process.

In the research by B. B. Musmade, R. K. Munje and B. M. Patre [7], a simple SMC strategy is designed based on the linearization of the nonlinear process model. This method is applied for the continuous yeast fermentation process. To broaden the scope of this method applications are extended to non-minimum phase behaviour processes. In conclusion, the proposed sliding mode controller can yield a better dynamic performance than conventional controllers. It is proved that the performance of the sliding mode controller is more robust against set-point changes and disturbances compared to conventional strategies.

In the research work by Hossein Nejatbakhsh Esfahani and Seyed Mohammad Reza Sajadi [8], SMC is developed for a class of nonlinear multi-input multi-output disrupted systems. In order to overcome the chattering problem and to ensure the tracking of desired trajectories, the authors proposed to combine an adaptive PD controller with the sliding mode. Based on the Lyapunov stability approach, the researchers suggested that their proposed adaptive sliding mode control scheme could guarantee global stability and the robustness of the closed-loop system with respect to disturbance.

In the research work by S. Mahieddine Mahmud, L. Chrifi-Alaoui, V. Van Assche and P. Bussy [9], the authors proposed a non-linear SMC with mismatch disturbances. The proposed method attenuates the effect of both uncertainties, external disturbances and eliminates the chattering phenomenon. The model of a hydraulic system is used to test the procedure.

The work by Aamir Hashim Obeid Ahmed [10] addresses controlling the speed of a separately excited DC motor. A separately excited DC motor is generally controlled by Proportional plus Integral (PI) controller. PI controller is simple but sensitive to parameter variations and external disturbance. Hence, for the robustness of Sliding Mode Control (SMC), especially against parameters variations and external disturbances, and also its ability in controlling linear and nonlinear systems; a separately excited DC motor sliding mode speed control technique is proposed in this paper. The simulation results showed that SMC is a superior controller than PI controller for speed control of a separately excited DC motor.

In the research work by Giuseppe Fedele [11], an identification method to estimate the parameters of a first order plus time delay model is proposed. Such a method directly obtains these parameters using a new linear regression equation. No iterations in the calculation are needed. A simple true/false criterion to establish if the hypothesis on the process type is correct can be easily derived. The proposed method shows acceptable robustness to disturbance and measurement noise as it is confirmed by several simulated experiments.

The work by Farzin Piltan, Sara Emamzadeh, Zahra Hivand, Forouzan Shahriyari and Mina Mirzaei [12], demonstrates the MATLAB/SIMULINK realization of the PUMA 560 robot manipulator position control methodology. This research focuses on two main areas, namely robot manipulator analysis and implementation, and design analyzed and implemented nonlinear Sliding Mode Control (SMC) methods. At present, robot manipulators are used in an unknown and unstructured situation and caused to provide complicated systems, consequently strong mathematical tools are used in new control methodologies to design a robust nonlinear controller with satisfactory performance (e.g., minimum error, good trajectory, disturbance rejection).

In the research by Sarah Spurgeon in the year 2014 [13], various canonical forms to facilitate design, have been described, and many numerical examples have been presented to reinforce the theoretical discussions. Of particular importance is the case of digital implementation, or indeed digital design, of sliding mode controllers.

In continuous time, discontinuous control strategies fundamentally rely upon very high frequency switching to ensure the sliding mode is attained and maintained. The introduction of sampling is disruptive. For example, switching of increasing amplitude can take place about the sliding surface.

In the research work by R. Saravana Kumar, K. Vinoth Kumar and Dr. K. K. Ray [14], the main objective was aimed at controlling the position of a field-oriented Induction Servo motor drive for a given reference input signal in a very efficient way. Their work was primarily focussed on designing a complete sliding-mode control system which would be insensitive to uncertainties, including parameter variations and external disturbances in the whole control process. They analyzed the design of an adaptive sliding- mode control system, which could adjust the bound of uncertainties in real time and also could reduce the chattering phenomena in the control effort using a simple adaptive algorithm.

The research by Chintu Gurbani and Dr. Vijay Kumar [15], addresses the designing of a controller using various types of sliding mode control strategies. Sliding mode control uses discontinuous control laws to drive the system state trajectory onto a specified surface in the state space, the so-called sliding or switching surface, and to maintain the system state on this manifold for all the subsequent times. For achieving the control objective, the control input must be designed with authority sufficient to overcome the uncertainties and the disturbances acting on the system.

In the research by Pushkin Kachroo and Masayoshi Tomizuka [16], a boundary layer around the switching surface was used to reduce chattering in sliding-mode control, and a continuous control was adapted within the boundary. The effects of various control laws within the boundary layer on chattering and error convergence in different systems were examined. New functions for chattering reduction and error convergence inside the boundary layer were suggested, which are discontinuous in magnitude only but not in sign. The internal model principle has been applied to generalize the design for the class of nonlinear systems being considered.

The research work by Yong Feng, Xinghuo Yu and Zhihong Man in 2002 [17], presents a global non-singular terminal SMC for rigid manipulators. A new terminal sliding mode manifold is first proposed for the second-order system to enable the wiping out of the singularity problem associated with conventional terminal SMC. The time taken to reach the equilibrium point from an initial state is guaranteed to be finite time. The proposed terminal SMC is then applied to the control of n-link rigid manipulators. Simulation results are presented to validate the analysis. a global non-singular TSM controller for second-order nonlinear dynamic systems with parameter uncertainties and external disturbances has been proposed. The time taken to reach the manifold from an initial system states and the time taken to reach the equilibrium point in the sliding mode have been proved to be finite. The new terminal sliding mode manifold proposed can enable the elimination of the singularity problem associated with conventional terminal sliding mode control. The global NSTM controller proposed has been used for the control design of an n-degree-of-freedom rigid manipulator. They presented simulation results to validate the analysis. The proposed controller can be easily applied to practical control of robots as given the advances of the microprocessor and the variables with fractional power can be easily built into control algorithms.

In the research by Goran Golo and Cedomir Milosavljevic [18], a new control algorithm based on discrete-time VSC theory was proposed. The basic feature of the algorithm is that trajectories reach the sliding manifold in a finite time, without chattering. Apart from stability, the robustness of the algorithm w.r.t. parameter uncertainties, as well as foreign disturbances, is considered. The authors established that robustness could be improved by reducing the sampling period. The theory was illustrated on a DC servo-position system. The realization of the proposed law requires knowledge of the state vector *x*. The control law has two modes. The first, non-linear mode ensures the reaching of the vicinity of the sliding hyperplane, in a finite number of steps. The second, linear mode ensures that the system reaches the sliding hyperplane in one step in the absence of external disturbances and parameter uncertainties. The linear mode is obtained by the state feedback pole-placement technique. The main feature of the proposed algorithm was robustness with respect to disturbances and parameter variations. Moreover, since a continuous function is in the vicinity of the control law, the system will be chattering free.

6. Future Directions

It has been established that SMC can be made useable in any type of non-linear process. So, future research in this regard can be an efficient process controller for industrial processes using SMC. The SMC can be effectively used in controlling the errors in industrial processes.

7. Conclusion

This review paper gives an overview of the concept of Sliding Mode Controller with a bibliographical survey of relevant background, practical requirements, the present state, and techniques. It is based on many research articles published from the past years. The citations listed here provide a representative sample of current engineering thinking pertaining to the wheeling of process control of non-linear systems.

The different process control techniques discussed here can be used for SMC. Process control systems (PCS) are pieces of equipment along the production line that can collect and transmit data during the manufacturing process. With its robustness properties, sliding mode controller can solve two major design difficulties involved in the design of a braking control algorithm: (i) The vehicle system is highly nonlinear with time-varying parameters and uncertainties; (ii) The performance of the system depends strongly on the knowledge of the tire/road surface condition [1].

For a class of systems to which it applies, a sliding controller design provides an organized approach to the problem of retaining stability and consistent performance in the face of modelling imprecision. For the wheel slip control system, the vehicle and brake system are highly nonlinear and time-varying systems. That makes a sliding mode controller ideal candidate for the application.

Acknowledgement

The author would like to thank all the anonymous reviewers for their contribution in the form of feedback to this paper.

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A Review on Optimal Operation of Distributed Network Embedded to Wind-Battery Storage System

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Abstract: ***Energy is a vital requirement for today's socio-economic welfare and development. But due to the continuous increase of the demand the conventional energy resources are depleting day by day and on the verge of extinction. Hence more renewable generation units are emphasised to integrate to the power network to supply the required demand. This incorporation of the distributed generation into the distributed network has the advantages of controllability, flexibility and tremendous potential if it can be exploited properly. However, due to their intermittent and unpredictable nature, there is a need for energy storages to ensure continuous operations, i.e., to meet the load all the time. There are many possible options for energy storage, but the most popular and technologically sound option is battery storage. Along with this battery storage system (BSS), a power conditioning system (PCS) has to be connected for generation of both active and reactive power from the BSS which in turn increases the overall installation cost of BSS. Moreover, the energy storage cost is a function of the storage device power, energy capacities and their specific costs depending on the chosen technology of optimization. Thus, profit from those renewable energy producers have to be maximized, and losses are to be minimized by using dynamic optimization techniques. But along with the advantages there comes the complexities due to the inclusion of distributed generation and the additional energy storages in the power system network. Moreover, it is highly critical to operate the vast system optimally. Hence there are lots of research had been done or are in process for finding the proper approach of optimization of the system. This paper presents a review of the current state of the optimization methods applied to renewable and sustainable energy source embedded with the Energy storage for maximization of the revenue obtained from the power trading to the network.***

Keywords: Distributed Generation (DG), Distributed Network (DN), energy storage, Battery storage system (BSS), power conditioning system (PCS),Dynamic optimization techniques, Energy Management System (EMS)

1. Introduction

Renewable Power Generation systems are being increasingly preferred for clean power generation, to reduce the dependency on fossil fuels and to cease greenhouse gas emissions. Many countries have implemented various terms and policies to promote renewable energy in the distribution network. Many researches have been recently carried out for making the wind farms dispatchable. This can be accomplished by integrating a Battery Storage System (BSS) with these wind farms [1]. It was shown that the only economically feasible BSS technology is Zn/Br [10]. With high Photo Voltaic (PV) and wind penetration in some regions, there is a surplus power available, which is utilized for charging the Battery Storage System during low demand and deliver power during high demand. From the consumers' point of view, use of a BSS can lower the electricity costs as it can store electricity bought at lower prices during off-peak, which can be used during peak load periods in the place of expensive power [7]. The potential of BSS can be well understood from Fig. 1.

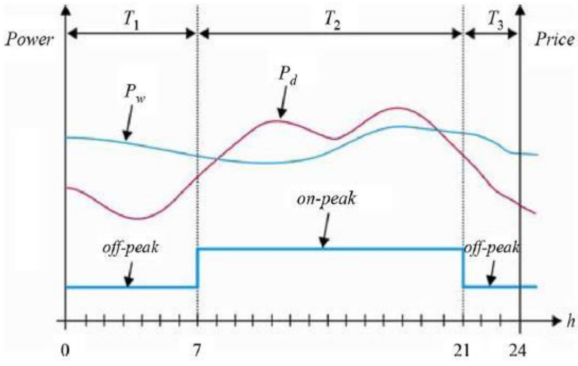

Fig. 1: Daily wind-demand power profiles and electricity price model

Fig. 1 schematically shows the daily demand and Wind Power profiles. It can be seen that, during time periods of T_1 and T_3 (off-peak), the excess energy can be stored in BSS. This stored energy can be used during the time period of T_2 (peak), in which the demand is more than the wind power penetration. In a research by A. Gabash and P. Li [2], a method based on genetic algorithms (GA) is applied to evaluate the impact of the cost of energy storage on the economic performance of a distribution substation .Thus by optimizing the daily /weekly scheduling of the renewable generating plants integrated with the BSS should be done in order to maximize the total revenue [1]. BSS should be connected to the AC power system through PCS which is a Flexible AC Transmission System (FACTS) device used for accommodating the bidirectional power conversion between AC and DC system.

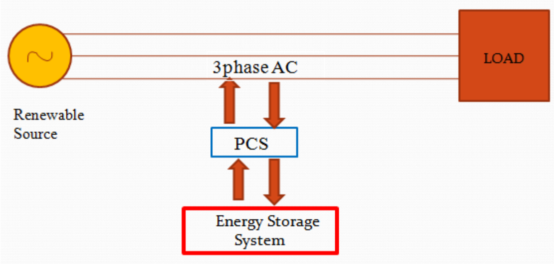

Fig. 2: Arrangement of Storage system and PCS

2. Optimization Techniques

The best suitable or the most acceptable design of all feasible conceptual designs can be said as the optimum design of a system. This process of designing the optimum system by satisfying some objective is called optimization; it follows a process or methodology of making something fully perfect, functional, or effective as possible; specifically by using the mathematical procedures. Simply, optimization is the process of maximizing of a desired quantity or minimizing of an undesired one [17]. Whereas, the various techniques used for designing the optimum model are known as the optimization techniques. In terms of Electrical Energy System, the optimized power system should minimize the fuel cost or minimize the losses, keep the power outputs of generators, bus voltages, shunt capacitors/reactors and transformer's tap-setting within their secure bounds and maximize the total profit.

Some of the classical optimization techniques are direct method, gradient methods, linear programming method (LP) and interior point method. Some of the advanced optimization technique includes simulated annealing, evolutionary optimization algorithms (Genetic algorithm(GA), Particle swarm optimization(PSO), Ant colony optimization (ACO), Estimation of distribution algorithm (EDA), Differential Evolution(DE), Evolutionary Strategy(ES), Evolution Programming(EP), Bacteria Forging Algorithm (BFA), Bee's colony Algorithm (BCA) etc.). The choice of suitable optimization method depends on the type of optimization problem. Due to the fast development of digital computers, there are major advances in optimization techniques. Techniques like GA and PSO have become very popular and powerful tools in power engineering to minimize the electricity cost in the electricity market from consumers' point of view and also to enhance the profit derived from power trading. The classical optimization techniques are also useful for single as well as multi-dimensional optimization problems, but there are some drawbacks and they are less effective and reliable compared to the advanced techniques; because unlike advanced optimization method, classical methods do not use the information gathered from previously solved points [18]. Moreover, in the gradient method, the algorithm terminates as the gradient of the objective function reaches very close to zero. The slope or gradient of the function indicates what direction to move locally. Thus, it uses the knowledge of derivative information to find the local optimum point, not the global optimal point [19]. Again, for the LP method, there lies the condition of both objective and constraints being linear. Thus, the classical methods are inferior for finding global optimum; moreover, they are highly sensitive to the initial conditions. This suggests that to solve the complex, non-linear, discrete, continuous or mixed variables, multiple conflicting objectives, discontinuity etc., as the power flow optimization problem of the power system, there is a need of some robust techniques. Hence, advanced optimization methods come into play. Among them, for the problems having a very large number of decision-variables and non-linear objective functions, Evolutionary algorithms are often used. The evolutionary algorithms are based on population-based search methods that incorporate random variation and selection. The first evolutionary-based optimization technique was the genetic algorithm (GA) [18]. Eventually, more optimization algorithms like Particle Swarm Optimization (PSO) [16], Ant Colony Optimization (ACO) and Estimation of Distribution Algorithm (EDA) etc. came into existence.

According to the characteristics of the evolutionary algorithm, one algorithm cannot be superior to the other in all kinds of cases. Hence, for a class of problem, one has to observe which algorithm is reliable to obtain an optimized result. Another popular approach of solving optimization problem is the implementation of the Algebraic Modeling Languages (AML) like General Algebraic Modeling System (GAMS) [25], Advanced Interactive Multidimensional Modeling System (AIMMS) [26], A Mathematical Programming Language (AMPL) [27], LINDO [28], etc. AML are high-level computer programming language, which uses different algorithms called solvers to handle different mathematical problems. They are also suitable for modelling of linear, nonlinear, mixed integer, large scale and complex optimization problems, as they are proficient in high-level mathematical computations. Hence, AML can easily be implemented to the power flow optimization problems.

3. Optimal Power Flow

The finding of the real and reactive powers scheduling of power plant in a way that it minimizes the overall operating cost of the interconnected power system by satisfying some set of operating constraints is known as the optimal power flow (OPF) problem. The OPF was first formulated by Carpentier in1962, and it was proved to be a very difficult problem during those days. There are commonly three types of problem in power system. They are load flow, economic dispatch and OPF, while economic load dispatch and load flow are the sub-problem of OPF. For a very large system, the modern trend is to use the metaheuristic algorithms to solve the non-convex, non-linear, complex OPF [20]. A metaheuristic algorithm is a higher-level procedure to find a near optimal solution; it guides the search space. These metaheuristics can be both local/ global search based. As OPF is population-based optimization, hence global search metaheuristics are applicable. Such global search metaheuristics include the evolutionary computation, GA, PSO, ACO etc. [21]. Even though, the cost of generation and real power generation can be found out using the versatile Newton-Raphson (NR) method. However, by using the developed Constraint, GA-OPF through crossover and mutation operations can further reduce the cost of generation [21].OPF is a large-scale, static optimization problem with both continuous and discrete control variables. The discrete control variables are the switchable shunt devices, transformer tap positions, and phase shifters and due to their presence, it becomes complicated to derive the problem solution. In the research by L. L. Lai, J. T. Ma, R. Yokoyama and M. Zhao [21], a simple genetic algorithm (SGA) is applied for OPF solution. The control variables taken in their work are generator active power outputs, voltages, shunt devices, and transformer taps. Complexity arises when the number of control variables increases. The GA-OPF approaches do not have the limitations of the conventional methods in the modelling of non-convex cost functions and discrete control variables. However, they do not scale easily to larger problems, because the solution weakens with the increase of the chromosome length, i.e., the number of control variables. Thus, the existing GA-OPF is limited to very small problems. So in addition to the basic genetic operators of the SGA [21], the advanced and problem-specific operators are used to enhance the performance of GA. The three basic genetic operators are parent selection; crossover and mutation. Thus with the incorporation of the problem, specific operators such as Gene Swap operator (GSO), Gene Cross Swap Operator (GCSO), Gene Copy Operator (GPO), Gene Inverse Operator (GIO) and Gene Max-Min Operator (GMMO) the GA can solve larger OPF problems [7]. But, unfortunately, recent researchers have identified some fault in the performance of GA [23]. Hence evolutionary computation PSO was introduced to solve the OPF problem for its simple concept and flexibility. It can be observed from some researchers, like the results obtained by M. A. Abido [24], that PSO technique is highly effective and superior over the classical techniques and genetic algorithm. In addition to these hybrid heuristic algorithms (i.e. use of two optimization techniques together) are also used for solving OPF problem in order to get better results [30]. Optimization of the power network can also be done using AML [25-29].

4. Optimization of a Combined System

The electrical power system is a network of a large number of electrical components used for supplying, transferring and utilizing power. Economically, electricity (both power and energy) can be bought, sold and traded. The profit derived from the power trading should be always more than all other costs (like generation cost, operation and maintenance cost etc.), which in turn will affect the electricity pricing. Hence, optimization plays a great role in such condition. Hence, ACOPF is solved every year for power system planning, every-day for the day-ahead market, every hour and in-fact for every 5 minutes [31]. OPF finds out the optimal solution to an objective function subject to the power flow constraints and other operational constraints such as generator constraints, thermal stability constraints and voltage constraints and many more according to the requirement. But, when the renewable generation units are integrated to the power network, the designing of an optimum model becomes more complex; because along with the renewable source, other auxiliaries will also be incorporated such as BSS, PCS etc. Hence, to find the optimal operation of such an integrated system, there may be a need for designing multiple objective functions. As a result, the complexities of the power system increases further.

5. Optimal Operation of Wind-Storage System

Energy storage is one of the efficient and effective solutions to store and use energy on demand. It provides flexibility throughout the grid and enhances stability, power quality and reliability of supply. Hence energy storage systems, when embedded with the renewable energy generation, provide a wide range of ways to manage power supplies and develop a more stable energy infrastructure, and as a result, the cost of energy for utility providers and consumers get reduced as well as it brings down the operating cost of generation. Despite, the optimal BSS capacity is closely associated with the shape of load curves and parameters of all generating units in a power system [3].

Energy storage systems are comprised of three main modules:

a) The Battery storage, i.e., BSS

b) The Power Conditioning System (PCS), which helps the energy the energy conversion from AC to DC or DC to AC

c) The control system that controls the operation of the energy storage system

Since several decades, the optimization techniques are applied to the power system problems, and there seems to be a competition among the optimization algorithms, applied to the growing complexity of power system planning and operations related problems [4]. Optimization of ESS includes the optimal operation of the storage system with the least losses during charging and discharging. Moreover, the losses during AC-DC conversion also should be less. For the Renewable Embedded Storage System (RESS) the optimal scheduling of generation should be done for supplying power demand to the network. In the work by A. Gabash and P. Li [1], the operation of Wind-Battery stations is considered which is composed of two main substations. First, a wind farm substation, which can dispatch power hourly. Second, a Battery substation in which its power and capacity are selected initially through simulation procedures for satisfying the electricity market requirements at the same time [1].

The wind farm (WF) is designed to generate the active and reactive power. During low demand, the excess power is used to charge the battery through PCS. While during high demand, the power to the network is supplied by the wind farm as well as the battery.

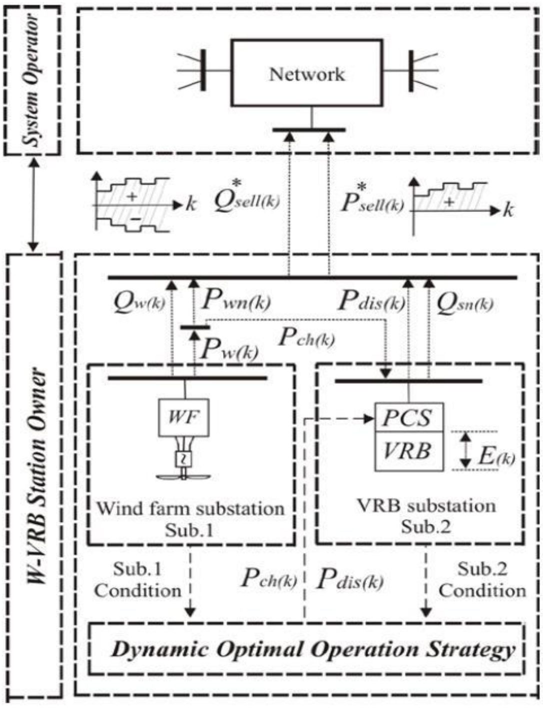

Fig. 3: Structure of the proposed W-Battery station and the total operating scheme

In Fig. 3, $P_{sell}(k)$ is the hourly active power to be sold to the electrical power system, $P_{ch}(k)$ is the hourly active power used for charging the battery substation and $P_{dis}(k)$ is the hourly active power discharged to the network from the battery substation respectively. Typically, the power factor (PF) of a wind farm is controllable from 0.95 inductive to 0.95 capacitive [5]. For simplicity 0.962 inductive power factor is assumed for the wind farm substation, which means absorbing reactive power, $Q_w(k)$ [1]. During charge/discharge processes, there are power losses. Generally, charging efficiency is assumed to be 80% and during the discharge, the efficiency is assumed to be 75% [6].

6. Profit Maximization

Besides optimizing the operation of the battery, if active power and reactive power are optimized separately using optimal power flow (OPF), then the total profit derived can be increased hence the efficiency of the power network can be improved [7]. The profit can be farther increased if combine Active-Reactive Optimal Power Flow (AROPF) is formulated in Distributed Networks (DNs), which is embedded with wind generation and battery storage, satisfying all the operational constraints. The solution provides an optimal strategy, which ensures the feasibility and efficiency and enhances the profit significantly. The optimized output obtained from the optimization of energy storage is implemented for optimizing the AROPF [2]. Generally, the solution for Active Reactive Optimal

Power Flow is obtained considering the fixed length of the charge and discharge cycle of BSSs. This can lead to a low profit because the profiles of renewable generation, demand and energy prices vary from day-to-day. Due to the dynamic behaviour of renewable energy sources (e.g., wind and solar), demand, and energy prices leads to a complex process and needs adaptive strategies to deal with. The integration of the BSS to the energy supply networks can help in controllability of charging and discharging time interval [10]. Hence, if the charging/discharging time of BSS can be controlled with respect to the input parameters, the profit output can be increased. The lifetime of a battery storage depends on a fixed number of charge/discharge cycles and days of operation. This can be represented by a replacement period (in years) by the formula [5]:

$$r = \frac{p}{n \times D}$$

where p is the total number of charge/discharge cycles in the lifetime, D is the annual operation days, and n is the number of charge/discharge cycles per day. Generally, the number of charging or discharging cycle is kept to be one in order to increase the replacement period of the battery and for optimal planning and operation [10]. Thus, the whole system of optimization wind battery embedded system can be represented by three objective functions.

6.1 Objective function for Energy Storage Optimization

When the ESS is embedded with a wind farm, the objective function can be formulated as [1]:

$$R_{max}=\sum_{k=1}^{24} [Cpr(k)Psell(k) - Cch(k)Pch(k) - Cdis(k)Pdis(k) - \beta\{\{(Pch(k+1) - Pch(k)\}^2+\{Pdis(k+1) - Pdis(k)\}^2\}] \ldots\ldots (i)$$

where $C_{pr}(k)$ represents a vector of hourly active power prices, $C_{ch}(k)$ is the charge operation cost, $C_{dis}(k)$ is the discharge operation cost. The objective is to maximize profit. The first summation term gives the total profit from active power trading in which the losses in the revenue by charging/discharging are subtracted. The second summation term is formulated to reduce the differences of control variables between two successive time intervals in order to evaluate the minimum constant reactive power capability. In the work by A. Gabash and P. Li [1], a weighting factor β is used to formulate a multi-objective model where the generation cost and system network loss is combined together.

6.2 Objective function for AROPF

In the work by A. Gabash and P. Li [2], the objective function for combined AROPF in DNs with embedded wind generation and battery storage is given by:

R_{max} = (total revenue from active power trading of wind farm) – (cost of energy losses) ….(*ii*)

Total revenue

$$= \sum_{h=1}^{T} Cpr(h) \sum_{i=1}^{N} [Pw(i,h)\, \beta_0\, (i,h) + Pdis(i,h) - Pch(i,h)$$

Cost of energy losses

$$= \frac{1}{2} \sum_{h=1}^{T} Cpr(h) \sum_{i=1}^{N} \sum_{j=1}^{N} G(i,j)(Vr^2(i,h) + Vim^2(i,h) + Vr^2(j,h) + Vim^2(j,h) - 2\{Vr(i,h)Vr(j,h) + Vim(i,h)Vim(j,h))\}]$$

Where G(i,j) is the real component of the complex admittance matrix elements. $P_w(i,h)$ is the active power of wind generation at bus i during hour h. $V_r(i,h)$ is the real component of complex voltage at bus i during hour h. $V_{im}(i,h)$ is the imaginary component of complex voltage at bus i during hour h. β_0 is the wind power curtailment factor, which is responsible for maintaining the capacity of the BSS (i.e., to spill a part of the power when the installed capacity of the BSS is not sufficient to accommodate the whole power or it may violate the other system constraints) [2]. The range of β_0 is 0 to 1. If there is no wind power $\beta_0 = 1$ or $\beta_0 \leq 1$

6.3 Objective function for finding the optimal time duration of charging and discharging of the battery

In another work by A. Gabash and P. Li [10], it is shown to be a two-stage iterative framework because the whole optimization problem is divided into two sub-problems. In each iteration, the integer variables (hours of charge and discharge periods) will be optimized with an efficient search method in the upper stage, while the continuous variables are handled by a Non-Linear Programming (NLP) solver in the lower stage. This forms a complex Mixed-Integer Nonlinear Program (MINLP). The optimization problem will have three additional integer variables (the three time variables) along with the continuous control variables for AROPF (i.e., active power charge, active power discharge of BSSs, reactive power dispatch of BSSs and wind power curtailment).

The objective function of general AROPF depends on the time variable. The function for maximizing the profit is represented by

$$R_{max} = F(x, u, t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (iii)$$

where *x* is the vector of state variables of the system, i.e., real and imaginary component of complex voltage at PQ buses, active and reactive power injected at slack bus and energy level of BSS. *u* is the vector of continuous control variables including active power charge/discharge of BSS and reactive power dispatch of BSSs. Lastly, *t* is the vector of the integer control variables, i.e., the number of charge/discharge hours per day. In eqn.(iii), the function F is the total revenue from wind power and BSSs minus the total cost of energy losses (includes the cost of active energy losses in the grid) [2].

Subjected to

$g(x,u,t) = 0$ .... (iv)

$x_{min} \leq t_1 \leq x_{max}$ ....(v)

$u_{min} \leq t_2 \leq u_{max}$ ....(vi)

where, g(x,u,t) in eqn.(iv) represents the equality constraints including active and reactive power balance equations (they are nonlinear terms). The energy balance equations for BSSs are also included in eqn.(iv). The inequality constraints in eqn.(v) and eqn.(vi) include voltage bounds, active and reactive bounds at the slack bus, and main feeder bounds. The operational constraints in eqn.(vii) and eqn.(viii) are also included in the inequality constraints.

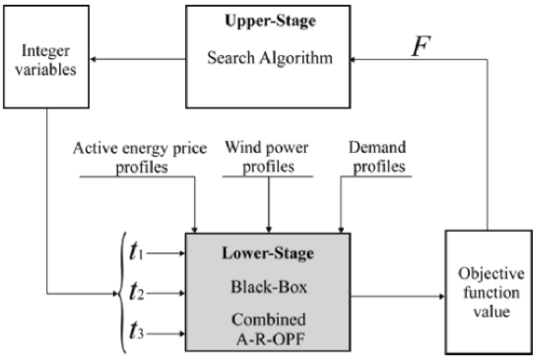

Fig. 4: Input-output model for the combined A-R-OPF with a search algorithm.

The two-stage model gives the sub-objective function for eqn.(iii). They are given by eqn.(a) and eqn.(b).

The upper stage solves the following problem.

Max F [x(t),u(t),t] .... (a)

Subjected to:

$t_1 + t_2 + t_3 = t_{max}$,where t_{max}= 24 and t_{min}= 0 ......(vii)

$$\left.\begin{array}{l} t_{min} \leq t_1 \leq t_{max} \\ t_{min} \leq t_2 \leq t_{max} \\ t_{min} \leq t_3 \leq t_{max} \end{array}\right\} \text{.....................} \text{ (viii)}$$

where t_{min} and t_{max} are the minimum and maximum bounds on time variables, respectively. The cycle of charge is determined by two integer variables representing the time periods (hours) of charge (t_1 and t_3). The cycle of discharge is defined by one integer variable representing the hours of discharge (t_2). As the daily operation of BSSs are considered, so t_{min}= 0 and t_{max} = 24 .

With the optimum value of t delivered from the upper stage, the lower stage solves the following NLP problem, i.e., AROPF becomes:

R_{max} = F(x,u) .... (b)

Subjected to

g(x,u) = 0 .... (c)

And inequality constraints are given by eqn.(v) and eqn.(vi). The solution of the lower stage provides the objective function value for the upper stage, where an update will be made for the next iteration until it reaches an optimum result.

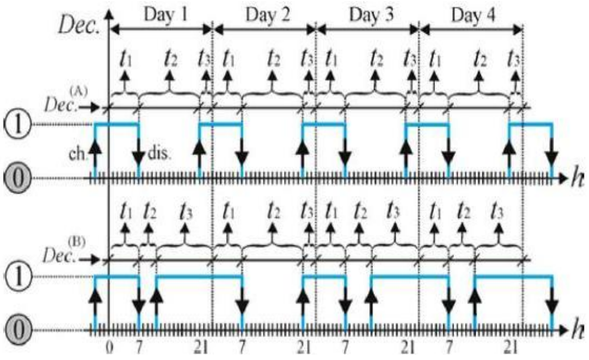

Fig. 5: Illustration for one charge/discharge cycle every day. A, and B stand for fixed and flexible operations of BSS, respectively

The model equations formulated by A. Gabash and P. Li, [1,2] for the system, describe the active power exchanges in the designed model as well as the change in the energy level in the BSS.

$P_{sell}(k) = P_{wn}(k) + P_{dis}(k)$ ……………...………. (ix)

$P_w(k) = P_{wn}(k) + P_{ch}(k)$ ..…………….…..……… (x)

where k = 1……..24, $P_{wn}(k)$ is the hourly active power delivered to the network by the wind farm, $P_w(k)$ is the hourly available wind power for a given wind speed.

The energy level of the battery is given by hourly energy balance equation in each storage unit. For optimization, it is commonly recognized that the energy level in the storage unit at the final time interval should be equal to that at the initial time point [1].

$E(k) = E(k-1) + \eta_{ch} P_{ch}(k)\Delta t - (1/\eta_{dis}) P_{dis}(k)\Delta t$
(for k = 1…….24) …………………..…………(xi)

Where,

E(k) = the energy storage level in the Battery substation in k^{th} hour
η_{ch} = charging efficiency of BSS
η_{dis} = discharging efficiency of BSS
The time interval Δt in research of A. Gabash and P. Li [1] is considered to be one hour.

Finally, the feasibility, capability and efficiency of the proposed model are verified with the IEEE 41-Bus test system. Taking into consideration of various equality and inequality constraints of the system for optimization of energy storage could be obtained by using the optimizing tools like General Algebraic mathematical system (GAMS), Genetic Algorithm (GA) or Particle Swarm optimization (PSO) etc. [8].

After solving the optimization problem for the objective given by eqn.(i), the optimal scenario of $P_{ch}(k)$ and $P_{dis}(k)$ can be obtained. Thereby, the reactive power from the Battery substation $Q_{sn}(k)$ [hourly available] can be calculated as follows [9]

$Q_{sn}(k) = \sqrt{(S_r^2 - P_{ch}^2)}$ if charging (k =1,..,24) …. (xii)

$= \sqrt{(S_r^2 - P_{dis}^2)}$ if discharging (k =1,..,24)..(xiii)

where S_r is the rated apparent power of the selected PCS, suitable for the battery station. Again the hourly reactive power available from the wind farm substation $Q_w(k)$ is given by

$Q_w(k) = P_w(k) \tan \Phi$ ……………..………….. (xiv)

where $Q_w(k)$ is set to work with the fixed power factor ($\cos\Phi = 0.962$) lagging (i.e. absorbing reactive power) [1]. Thus, the available reactive power to be sold to the electrical power system $Q_{sell}(k)$ can be calculated using relation:

$Q_{sell}(k)=Q_w(k) + Q_{sn}(k)$ …………………...….. (xv)

Therefore, the reactive power capability from the wind-battery station can be controlled using suitable PCS [1]. This reactive power can satisfy the local reactive power requirement of the wind farms and provide sufficient, constant and fully controlled reactive power to the electrical power system. In addition, it can also be used in a hybrid reactive power sources system by dynamic optimal operation at the W-B station. The reactive power could also be sold to the electrical power system for increasing power quality, voltage regulation, power losses minimization etc. Moreover, it increases the individual profit of wind farms through their reactive power compensation capabilities. Hence, the necessity of installing other reactive power compensators such as Static Synchronous Compensator (STATCOM) and Mechanically-Switched Capacitors and Reactors (MSCR) will get reduced in future. The optimization problem that is defined can be solved under the MATLAB environment, using FMINCON function [1], which can find a minimum/maximum of a constrained nonlinear multivariable function.

When a combined problem is formulated for active-reactive optimal power flow (A-R-OPF) for DNs with embedded wind generation and battery storage the objective was to maximize the total profit meanwhile the maximization of the amount of available reactive power. It was shown by A. Gabash and P. Li [2] that a large amount of reactive power can be achieved by an optimal operation of Wind-battery system embedded to DN. The formulated equations of the system show it to be a highly Non-Linear system; hence the Newton Raphson Power Flow Method is most suitable for finding the bus voltages of the required system. However, the initial values in the A-R-OPF method also has an impact on both the feasibility and computational efficiency of the system [2]. Hence the initial values are generally chosen to be a flat start for all computations, i.e.,
$P_{ch} = P_{dis} = Q_{disp} = V_{im} = P_s = Q_s = E = 0$
Whereas
$V_r^{(0)} = 1$

For different initial values, the solution converges to the same results, but the CPU time is different. Only when the initial values are very far from the flat start, a convergence problem may occur. The problem of AROPF in the work of A. Gabash and P. Li [2] with the objective function, as shown in eqn.(ii), is solved by using GAMS satisfying all the operating constraints. In addition, the NLP solver or algorithm used for solving the AROPF is CONOPT3, which is suitable for solving models with highly nonlinear constraints.

But in AROPF, even though charging-discharging power is flexible, the battery operation was restricted as the charging/discharging time of the battery was considered to be fixed. So the A-R-OPF method is extended by developing flexibility in the battery management system. This can be accomplished by optimizing the lengths (hours) of charge and discharge periods of BSSs for each day (24 hours). This, together with the A-R-OPF formulation, leads to a complex mixed-integer nonlinear programming (MINLP) problem, which cannot be readily solved by available approaches. GA has been successfully applied in solving many optimization problems in power systems, especially when both integer and continuous variables are present. The authors Anastasios G. Bakirtzis *et al.* [7] presented an enhanced GA for the solution of OPF with both continuous and discrete control variables. Since all these methods treat the continuous and integer variables simultaneously, they are not suitable to be used for the large-scale complex MINLP problem framework to decompose the optimization problem. Thus, a two-stage model is designed represented by (i) and (ii). In the upper stage, the time variable (i.e., hours of charge and discharge periods) are optimized based on the day-to-day profiles and delivered to the lower stage. In the lower stage, the A-R-OPF problem is solved by a Non-linear programming solver and the resulting objective function value is sent to the upper stage for the next iteration.

The search method for selecting the optimal time interval is a complex problem. It is demonstrated with the help of a search space shown in Fig. 6(a) and 6(b) [10].

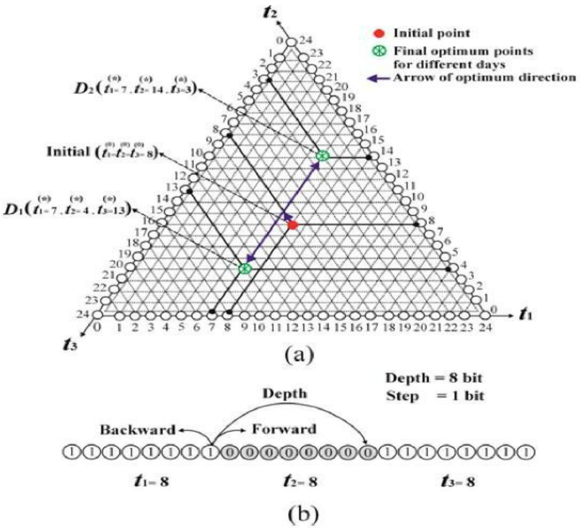

Fig. 6: (a) Illustration of the search space (b) String-structure.

In the search space, there is a total of 325 combinations as can be seen from Fig. 6(a). At first, an initial combination is selected (say $t_1 = t_2 = t_3 = 8$, i.e., at the center of the triangle) and this initial combination is provided to the lower stage for evaluating the objective function then the fitness value is recorded. Then keeping one of the variables fix (say t_3) and sweeping another variable (t_1) bit by bit backwards or forward from its initial value, different combinations are set. For each string, different fitness is recorded and among them, the best is selected for t_1. Then again, keeping t_1 fix for that value, sweeping is done with t_3 and the best value, which is obtained from it, is the best string found; its fitness represents the optimal operations for a specific day. Thus, the optimal lengths of charge/discharge cycle of BSSs for daily operations or even multiple days can lead to a considerably higher profit in comparison to that from a fixed operation strategy [10].

7. Conclusion

Many power related issues influence the operation of the Distributed Network (DN); and when Wind-Battery system is embedded with DN, the system becomes more complex to carry out the optimal operation of the network. Thus, many studies are done or still going on to find the most acceptable and feasible optimization technique that could be implemented to the power system for deriving the optimal operation. It can be concluded that the choice of suitable optimization method totally depends on the type of optimization problem formulated. In the case of deriving an optimized result of a wind-battery embedded system integrated into the power network, the problem is divided into parts then optimization is applied to maximize the profit of the overall system. Moreover, Energy Storage facilitates many advantages for optimal operation of the power network and has a great impact on profit maximization, specially when the generation is unpredictable. As the input parameters of the network are variable, a flexible and adaptive optimized operation strategy of storage systems can control the power flow and reduce the power losses, thereby enhancing the derived revenue from the power trading to the network. However, there is a very limited number of studies done related to the storage systems in grids such as design, dimension, location, operation planning and control of BSSs [10]. Hence, there lies immense opportunities and potential of BSS yet to be explored in the field of optimal power flow, which if explored will be promising in the future energy networks.

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Design of Electronic Load Controllers of Induction Generators used in Micro Hydro Power Schemes

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Abstract: ***This paper describes the use of Electronic Load Controller on micro hydro power scheme in which no separate penstock is required to control the speed of the flow of water. The Electronic Load Controllers (ELC) is an electronic device in which the output of the generator can be maintained constant instead of changing or fluctuating user loads. The ELC maintains a constant generator output by introducing a separate load called ballast load which absorbs the load required by the consumer. This paper also explains and demonstrate a simulation model of an ELC.***

Keywords: Electronic Load Controller (ELC), Micro hydro Scheme, Dump loads or ballast load, self-induction generator, simulation

1. Introduction

Power is one of the fundamental infrastructures all over the world. In the whole wide world, the requirement of electrical energy is increasing day by day. Apart from all the energy sources, renewable sources of energy, which include solar energy, biomass, wind, tidal, geothermal energy and hydroelectric power, play a very important role in resolving the problem of electrical energy supply in many applications. Micro hydroelectric power plants are considered to be the most economical, friendly technology and renewable source of energy, which is helping people in remote or rural areas that do not usually have access to electricity to have a sustainable energy supply [1].

Micro hydro power plant is a type of hydroelectric power plant, which produces up to 100KW of electricity by the implementation of the flow of the water. Due to the higher cost of transmission lines, micro hydro power plant fulfils the demand in energy supply especially in rural areas, which are not connected from the national grid. A micro hydro power plant is always designed at a lower possible cost. Therefore, Electronic Load Controller (ELC) is used instead of a conventional governor. Since the conventional governor is made using mechanical and hydraulic governors to control, the flow of water are uneconomical, high cost, difficult to maintain and construct especially in rural areas. Thus, Electronic Load Controllers the best way of controlling the output of the generator. Similarly, Electronic Load Controllers also increase the simplicity and reliability of Micro hydro power plant [2-3].

2. Electronic Load Controllers (ELC)

Electronic Load Controller is a new technology that was developed during the 1980s. Electronic load controllers control the load on the generator and its main objective is to hold the turbine and generator output at a constant speed instead of fluctuating user demand or water flow. This is achieved by introducing a separate electric load, called ballast load, which absorbs the load required by the consumer. In the case of ELC, if there is an increase in electricity demand, the amount of ballast load is switched OFF. Accordingly, if there is a decrease in electricity demand or an increase in the water flow, the output frequency rises up to a higher level due to the increase in speed of the turbine and generator. Thus, the ELC senses this higher frequency change; the ballast load will have exactly the same amount of power to keep the total load on the generator constant [3].

At full power, ELC is led to run the turbine and generator, or the power can be set manually or possibly at a manually set partial power, and electric load can be kept constant in order to attain the right speed. The function of this ELC is similar to that of the mechanical speed governor as it acts as a mechanical brake and the only difference is that ELC used electric braking. The ELC can be used to sense voltage rather than frequency since the generator is an induction type generator and does not have any internal voltage regulation. So, ELC is much better to use as a voltage regulator [6].

The power devices such as relays, thyristors, MOSFETs, or IGBTs can be used to control the dump loads. With the use of relays, a very basic slow/on/off control can be done, resulting in deterioration of the relay and unstable speed. Some operations by using thyristors are: Simple slow/on/off, individual half cycle control, individual full cycle control method, and phase control method within each half cycle are also used. With the use of MOSFETs or IGBTs, over and above the already mentioned tasks, a high-frequency pulse width modulated control can be implemented. Comparing the uses of IGBTs and MOSFETs, IGBTs have a better power handling to price ratio, while MOSFETs can be used to reduce the size of filter components, i.e., it can work at a higher frequency. By the implementation of all these methods, a constantly changing load on the generator can be attained. The change may be slow or fast but always happen, and that translates into a poor power factor, in which it can be overcome by maintaining an oversized generator. When many dump loads are used, this problem is becoming small; but such control with a single dump load is not encouraged to use. Instead, when high-frequency pulse width modulation is used with proper filtering, this problem can be disappeared.

Some of the advantages of ELCs over mechanical governors are that they are cheaper, quicker and more robust. Similarly, other advantages of electronic load controllers are that they do not require maintenance, as no moving part is required. Their disadvantage is only a waste of water, making them less suitable in case of water shortage, which implies the essentiality of a reservoir in this case [3].

3. Types of ELC Designs

The main type of ELC designs are as follows:

(i) Binary load regulation

(ii) Phase angle regulation

(iii) Pulse width regulation

(iv) Controlled bridge rectifier

(v) Uncontrolled rectifier with a chopper

- ***Binary load regulation*****:** In this case, the ballast load is made up from a switched combination of the binary arrangement of separate resistive loads. Similarly, the total resistive load is divided into a different number of elements wherein the system is bulky, prone to failure, and less reliable [3].

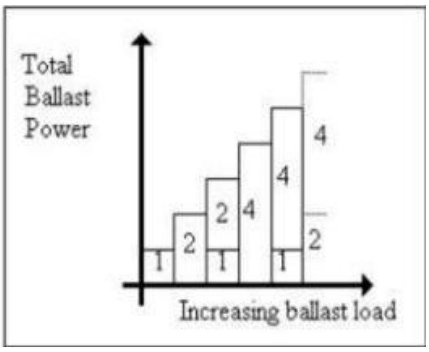

Fig. 1: Binary weighted ballast load [3].

- ***Phase angle regulation*****:** In phase angle regulation, the ballast load consists of a permanently connected single resistive load circuit, which is of magnitude equal or slightly greater than to the full load rated output of the generator. The firing angle of present power electronics switching device such as TRIAC can be adjusted to detect the change in the consumer load resulting in the change of the average voltage. Similarly, in a phase-controlled thyristor-based load controller, as the consumer load is changed from zero to full load, the phase angle of back-to-back-connected thyristors is delayed from 0 to 180. Due to a delay in firing angle, it demands reactive power loading and introduces harmonics in the system. So, it further requires complicated driver circuits [5].

- ***Pulse width regulation*****:** In this type of ELC design, firstly the AC voltage rectified and dump load is then switched ON and OFF with a variable duty cycle. PWM control can have a fast response; and compared to other schemes, they usually have smooth speed control [5].

- ***Controlled bridge rectifier*****:** In the controlled bridge rectifier for single-phase, a firing angle is changed from 0 to 180 and for three-phase, a firing angle is changed from 0 to 120. Similarly, in this scheme, it requires six thyristors and their driving circuits. Hence, it is also complicated, introduces harmonics, and demands reactive power [7].

- ***Uncontrolled rectifier with a chopper*****:** It consists of an uncontrolled rectifier with a chopper [a self-commutating device such as an Insulated-Gate Bipolar Transistor (IGBT)] in series with a dump load. Some of the advantages of this type of ELC design is that it has only one switching device and its required driving circuit. So, this scheme is said to be very simple, cheap, rugged, and reliable. It does not demand reactive power and generates a low value of harmonics. Similarly, this scheme is inexpensive and compact, as it requires only one dump load [7].

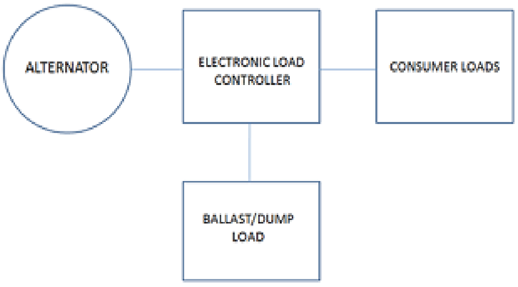

Fig. 2: Control strategy of ELC [5].

4. Design of Electronic Load Controller

In this case, ELC is designed with the used of an uncontrolled rectifier and chopper with a series “dump” load.

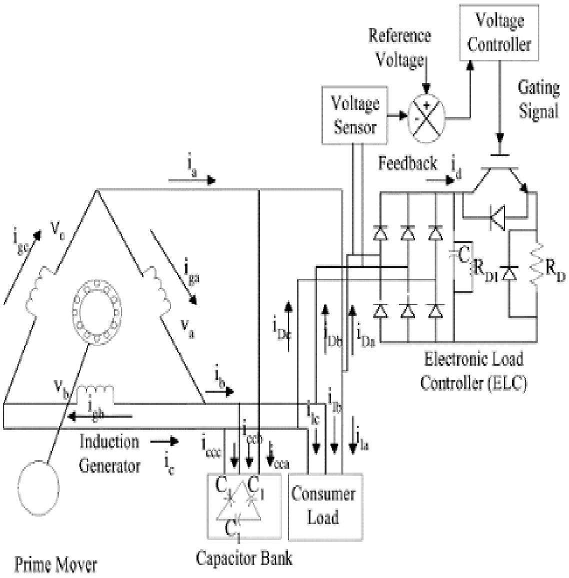

Fig. 3: Electronic Load Controller (ELC) [7].

Based on the design the ELC consists of an uncontrolled rectifier, a filtering capacitor, chopper, and a series resistor dump load. In this case, for the self-excited induction generator, ac terminal voltage is converted to dc by the used of an uncontrolled rectifier. A filtering capacitor (C) is used to smoothen the dc voltage because the uncontrolled rectifier output has ripples. In this circuit, an IGBT is also used as a chopper switch. The chopper switch is then turned ON when the consumer load on SEIG is less than the rated load and turns OFF when consumer load on the self-excited induction generator is at rated value. When the chopper switch is turned ON, and the current is allowed to flow through the dump load and consumes the difference of the generated power and the consumed power (difference power = generated power - consumed power), resulting in obtaining the constant load on the self-excited induction generator. Hence, constant voltage and constant frequency can be obtained at the load [7].

5. Simulation

Alex Jose and Dr. Jayaprakash P. [7] presented a simulation of the electronic load controller (ELC) has been done by using the simulation software MATLAB. Their MATLAB Simulink model of ELC for self-excited induction generator is shown in Fig. 4.

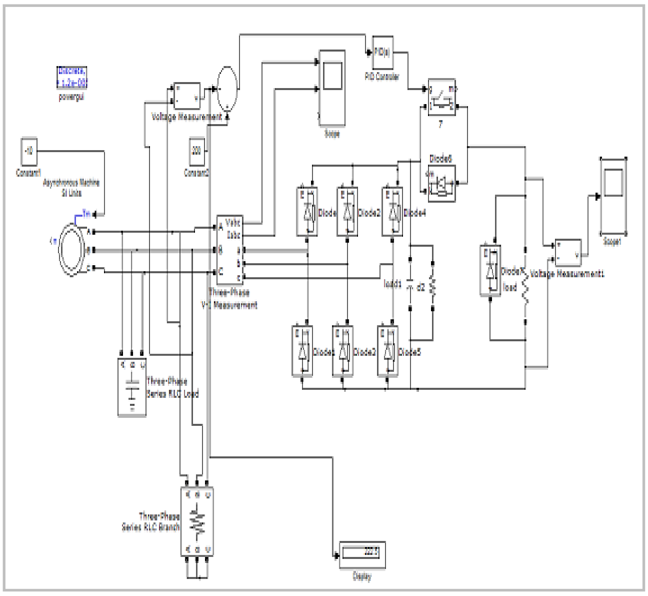

Fig. 4: MATLAB model of ELC connected self-excited induction generator [7].

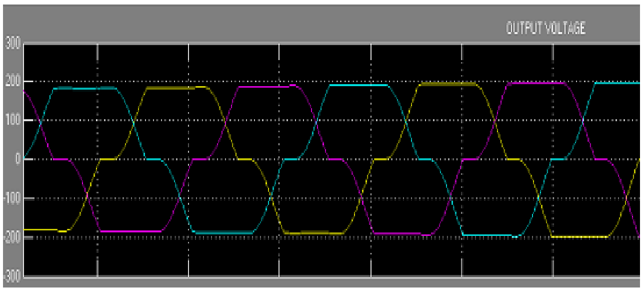

Fig. 5: Simulation results of ELC connected self-excited induction generator [7].

6. Conclusion

This paper presents an exclusive review of the analysis and design of electronic load controller. ELC eliminates the use of conventional governors resulting in making the system more reliable, efficient and economical. Therefore, ELC is the best way of controlling the output of the generator, as conventional governors are uneconomical and difficult to maintain and construct. The Electronic load control (ELC) was simulated, and the result of ELC connected self- excited induction generator is obtained by using MATLAB simulation software.

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Grid Connected Renewable Energy Sources and Net Metering: A Review

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Abstract: ***In this paper, the constraints of a grid connection are presented along with some of the solutions to the problems as proposed by various researchers. Non-renewable energy sources are getting exhausted day by day. There is a need for alternative sources of energy. In this paper, various constraints in the incorporation of grid-connected renewable energy sources and the required solution are discussed. The concept of net metering and associated challenges are presented in this paper.***

Keywords: Renewable Energy Sources, grid, net metering, grid connection

1. Introduction

Renewable energy (RE) is the energy that can be used again and again. With the increase in the demand of energy, the prime concern today is the availability of the source of energy, which is reliable. Conventional energy sources are nonrenewable and will be completely exhausted someday. Therefore the need for utilization of renewable energy is felt. About 80% of the world's total energy depends on fossil fuels. Use of fossil fuel is expected to rise by 1.5% annually by 2030 leading to 2.2% CO_2 emission [1]. However, fossil fuels are going to deplete soon [2,3]. Renewable energy contributes to energy system de-carbonization, security of energy in the long run, and expansion of energy to new energy consumer [4]. RES contributes 14% of the world's total energy demand [5]. RE can be used as an alternative energy source. It is primary, domestic and clean energy source [6,7]. By 2100, the contribution of energy by RES is expected to increase to 30%-80% [8]. Proper energy harnessing techniques are to be developed to achieve more energy from Renewable Energy Sources (RES). RES can be followed by net metering to achieve the process of utilization of electricity in a more economic manner. Energy generated from RES can be used to meet the household electricity demand for that duration of time or period when RES are available to produce energy. For the remaining period when RES cannot be used, electricity can be drawn from the grid. Electricity pays to the consumers, who feedback the surplus electricity produced from RES back to the grid. This process not only reduces electricity bills but also saves electricity that can be used some other consumer in need.

2. Grid Connected Renewable Energy Sources

A) Optimal Power Flow

Electricity generated from renewable sources may be needed to be transported over some distances, as they are not location specific. They lack the flexibility needed in balancing supply and demand. RES cannot be considered as an isolated node of energy network as it requires coordinated efforts from planning stage to power generation, distribution, storage and consumption [17]. Various constraints have to be solved in order to achieve optimal power flow between grid and RES.

B) Constraints in incorporation of RES

Factors that affect the integration of RES in the grid are [17,29,30]:

- Stability and Timing,
- Voltage imbalance,
- Effect of reactive power regulation,
- Flicker effect,
- Harmonic and inter harmonic voltages and currents,
- Voltage fluctuations in the point of common coupling,
- Need for power factor improvement,
- Intermittency, storage and capacity factor,
- Infrastructure for RES and suitable location,
- It requires a large amount of conventional backup,
- It requires huge energy storage to compensate for the natural variation in the power generated.

The role of government in uplifting RES through energy policies and supporting policies for deploying renewable energy on a large scale is observed [17]. Direct policies promote renewable energy, indirect policies influence incentives and barriers for renewable energy [31].

3. Solutions to the Problems of Grid Connection

Synchronization can be defined as minimization of aby variance in voltage, phase angle and frequency between the RES generator and grid supply.

Grid synchronization methods are as follows [35-48]:

(i) Zero crossing detection
(ii) Kaman filter
(iii) Discrete Fourier Transform
(iv) Nonlinear least square
(v) Adaptive Notch Filter
(vi) Artificial Intelligence
(vii) Delayed Signal Cancellation
(viii) Phase Locked Loop
(ix) Frequency Locked Loop

Some of the recommendations to achieve synchronization are [22]:

- Development of an efficient method for variation in phase angle and frequency with fair dynamic performance during voltage depression and harmonic variation.
- A synchronization scheme based on the estimation of grid voltage and frequency should be given more attention.
- A robust method with advanced features for efficiently injecting power into the power grid with low total harmonic distortion of current is needed.
- A method to achieve uninterrupted operation of the RES in abnormal utility voltage conditions is to be developed.

The active power quality can be improved by optimal usage of renewable sources and avoiding the usage of battery by replacing it with a solar energy unit. Dynamic active power filter fed by solar energy unit gives power to the load during power fluctuation from the grid side [20].

Maximum power point tracking is a technique used to improve the photovoltaic system efficiency [21]. MPPT are power electronic DC-DC converters [5,27] that enable the solar panels to operate with current voltage parameters that will always produce highest output power from the PV system to the load irrespective of external conditions [26,28].

Solar trackers are mechanical rotors that guide PV panels in such a way that the panels are constantly positioned at an angle that allows them to receive the most sunlight [4].

Transformer-less inverters are of small size and have light weight, more efficient and simple. By removing the transformer, efficiency of 96%-98% can be obtained. The drawback is ground currents are introduced here, and research can be done to obtain ways to remove ground currents [4].

Inverters must be designed in such a way that they operate at power factor equal to one, hence reducing the reactive power supplied to the grid. Inverters must also keep total harmonic distortion of the current supplied by grid-connected PVs to a minimum value. Algorithms for optimal power flow control in grid-connected PVs are:

- Feedback linearization control
- Phase lock loop control
- Extended direct power control
- Power factor control

A stable frequency is required for operation of grid-connected PVs and an inverter is needed to disconnect from the grid when its frequency becomes unstable. To restore nominal frequency real power must be provided to the grid as soon as possible. Frequency is constant when active power is equal to load demand at any given time. Shortage of active and reactive power must be compensated at least until energy supply and demands are balanced [16].

Fluctuation control in the output of wind and solar energy is provided by batteries. Batteries provide energy to the load during low power generation and store energy during excess power generation, and thus smoothen out the output of an irregular generation source. Some of the common battery technologies used are:

- Lead-acid technology
- Nickel Iron, redox flow and sodium Sulphur batteries
- Lithium-ion technology [19]

Lithium-ion batteries have the highest energy density and are costly. Work can be done to optimize the energy density of batteries and make them cost-effective. Lithium-ion batteries have high cell voltage, no memory effort, low cell discharge rate and flat discharge characteristics [32].

Conventional real-time optimal power flow method and day ahead optimal power flow method neglects the impact of variability. There are some modified methods that propose an evaluation of best fitting participation factors by considering minute-to-minute variability of solar and wind load for real time-optimal power flow and every 15-minute variation of the load for day-ahead optimal power flow for the scheduling time period. Voltage, reactive power and line flow constraints are included for all the intervals in both real-time optimal power flow and day ahead optimal power flow and voltage stability index is calculated.

4. Net Metering

Net metering uses a bi-directional meter that records the amount of electricity drawn from the grid or supplied to the grid. The electricity provider pays the consumer for supplying back the additional amount of electricity produced back to the grid. The consumers have to pay only for the amount of electricity taken from the grid in case the electricity from RES is not sufficient to meet the demand.

Buildings lead to the emission of CO_2 .Reduction of excessive use of energy and emission of greenhouse gases is needed. Installation of meters and sensors, for monitoring the use of energy and indoor environmental conditions, is needed. In the case of metering equipment, lots of work is done to enhance it. Many solutions are available which makes it difficult to select the best one. Accuracy, ease of development, communication protocol, granularity, cost and availability are some of the factors that affect the selection of sensing and metering solutions. Both wired and wireless technologies are used for data transmission in net metering. Wireless technologies are cheaper and wired technologies are more secured. Widely used communication and network technologies for net metering are Zigbee, power line carrier, Modbus, GPRS, GSM, Wi-Fi, M Bus, BACnet, Ethernet etc. Future challenges in this area being interoperability, lack of ICT infrastructure, cost, MEMS sensor Technology [23].

Test of the feasibility of net metering is very important. Simple net metering cannot serve diverse consumers. More scalable, feasible and economically acceptable net metering approaches serve the purpose [24]. Net metering is in its budding stage in India. Cities like Delhi, Bengaluru, Kolkata has drafted their initial net metering policy [25,9]. However, there is a need for change in energy policies to realize the benefits of the smart grid in its full potential [10]. Now-a-days, 110 KW standalone rooftop solar PV system with uninterrupted power supply covering a building is available, which provides total output to the grid of 1927.7 kW hour, an annual yield of 931.6 kW hour and an average output of 160.64 kW hour per month [11].

Solar PV systems on bright rooftops with 75 Wp solar modules are capable of generating about 1000 MW of electricity through standalone PV systems. With solar modules of high capacity (210 Wp), electricity generation can be greater than 1500 MW [15].

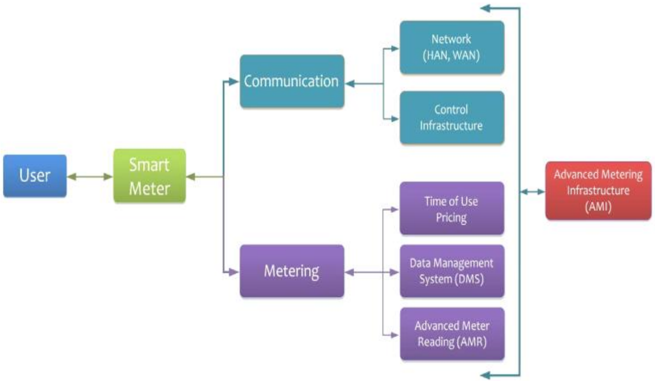

Fig. 1: Smart grid perspective with all components [12]

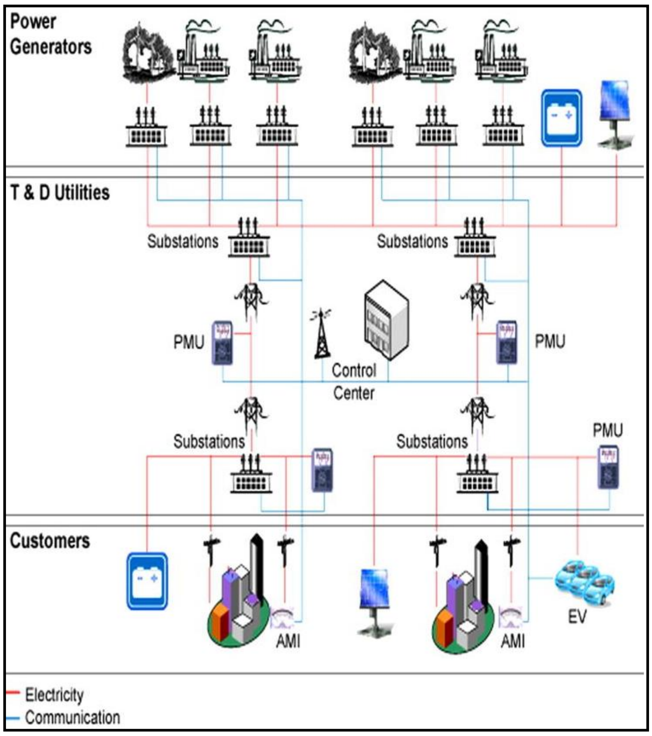

Fig. 2: Power generation, control, and measurement diagram across the distribution network and consumers [14]

5. Conclusion

It is observed that with the high increase in demand for energy the possibility of scarcity of energy in the future is increasing. Renewable energy sources can be cited as one of the solutions to meet the energy demand of diverse consumers. At present, the contribution of renewable energy sources as compared to the conventional energy sources is less. However, energy-harnessing methods from these sources are yet to be developed and are needed to be improved to a great extent. Production of energy from renewable energy sources, by maintaining optimal power flow is to be achieved.

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Advanced Control Methods of Induction Motor: A Review

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Abstract: ***In this paper, various types of advanced control methods of the induction motor are discussed, and a comparision between these methods have been brought out. This paper also discusses about the application areas of these new methods. The objective of this review is to conclude which method is the best control scheme among all of these methods. The related block diagrams for various control schemes are also illustrated along with various steps involved in the implementation of those schemes. Advantages and disadvantages of the schemes are also presented.***

Keywords: Scalar Control, Vector Control, Direct Torque Control, PID controller, SMC Control

1. Introduction

In 1891, Nikola Tesla presented prototype of a poly-phase induction motor at the Frankfurt exhibition [27]. From that onwards, the Induction motor is widely used in many residential, industrial, commercial, and utility applications like Large fans, centrifuges, long conveyor belts, electric vehicles, water pumping etc. Induction motors are so popular because of its low manufacturing cost, wide speed range, high-speed efficiencies and robustness [1]. All such application required constant speed drive as well as variable speed drive. There are various conventional methods for variation of rotor speed. Some of them are inserting a rotor resistance in series with the three-phase winding [2], changing the no of stator poles [3], Stator voltage control [4], Supply frequency control [5] etc. All of the above control methods are not economical and less efficient. In the applications where accurate control is required, they are not feasible. So looking for an advanced control scheme is necessary. Due to the development of power electronics devices, speed can be controlled to a larger extent. Even though, efficiency has not much improved. In order to achieve all such desired condition of a drive, it requires advanced control schemes. So, new controlling methods are being built up nowadays. Some of them are not yet practically implemented.

2. Background Details

Three phase Induction motors are the self-starting motors. It is also a constant speed motor. Hence it is difficult to control its speed; while controlling the speed of induction motor, it has to sacrifices its efficiency and power factor.

In electrical ac machines, there are two speed-related terms - synchronous speed and rated speed. Synchronous speed is the speed at which magnetic field rotates. It is theoretical speed when there is no load on the shaft and friction in the bearing. Synchronous speed depends upon the two factors- frequency and pole.

Synchronous speed in RPM, $N_s = 120f / P$ ….... (1)
Where f = frequency (Hz)
P = No. of poles

Rated speed is the maximum speed of the motor, at which motor is allowed to achieve to work properly. It depends upon the power input to the motor.
$N = N_s\,(1\text{-}s)$ …………………………………. (2)
Where N_s = Synchronous speed, s = slip
N = speed of rotor

The percentage difference in synchronous speed and shaft speed is called slip, given by

$s = (N_s - N_r) / N_s$ …………………………….. (3)
Where N_s = Synchronous speed
N_r = Rotor speed

Shaft speed of Induction motor is always less than the synchronous speed when driving the load.

Torque produce by Induction motor depends upon the following parameters - rotor EMF, rotor resistance, inductive reactance and synchronous speed.

$$T = \frac{3}{2\pi N_s} X \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2} \quad \text{………………. (4)}$$

Where, E_2 = the rotor emf
N_s = the synchronous speed
R_2 = the rotor resistance
X_2 = the rotor inductive reactance

At the starting stage, torque must be high and speed will be less. In the running stage, speed is high and torque reduces. Hence, torque can be increased by varying the above parameters. By varying rotor resistance and inductive reactance, it adds extra cost; also it can be applied only in the slip ring induction motor. So, the best way for controlling torque is voltage.

$$N_s \infty \frac{f}{P} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

From the above equation, it can be seen that synchronous speed is directly proportional to frequency and inversely proportional to the pole number. The number of poles of a given machine is fixed, so the speed varying can be done by varying frequency.

3. Control Methods of Induction Motor

3.1 Scalar Control (V/F)

The Scalar Control method is an open loop control scheme, in which no feedback system is required. Synchronous speed can be control by varying the supply frequency f. The voltage induced in the stator is directly proportional to ϕ, where ϕ is the air-gap flux. As we can neglect the stator voltage, we obtain terminal voltage directly proportional to ϕ. Thus reducing the frequency without changing the supply voltage will cause an increase in the air-gap flux, which is considerable. Hence, whenever frequency is varied, the terminal voltage is also varied in order to maintain the V/F ratio constant. Thus by maintaining a constant V/F ratio, the maximum torque of the motor can keep constant for changing speed [6,7].

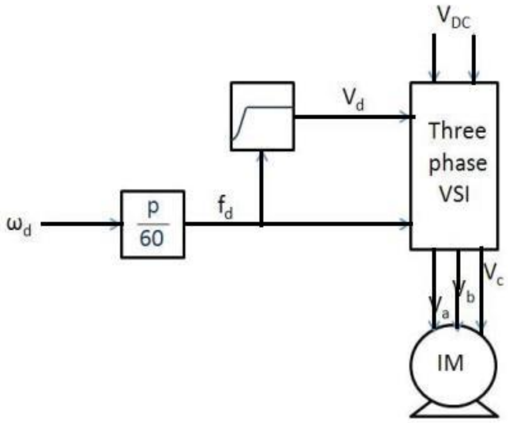

Fig. 1: Open loop V/F control of IM [8]

3.2 Vector control

Vector control is controlling of an ac motor similar to a dc motor by the use of feedback control. It is compulsory to perform d-q transformation [9,10,11,12]. By this method, fast torque response can be achieved.

Steps followed in vector control:

1. d-q transformation
2. Speed estimation
3. Generating error signal from reference and measure speed
4. The error signal is fed to the controller to generate a torque reference signal
5. Calculation of current for d and q axis, the position of rotor flux and transformation into a real model
6. Generation of PWM signal for an inverter.

There are two methods to detect rotor flux position:

i) Direct vector method
ii) Indirect vector method

i) Direct vector method

In this method, flux sensing coils or the Hall devices are used to measure the flux. It adds extra cost, also the result is not highly accurate [13,14].

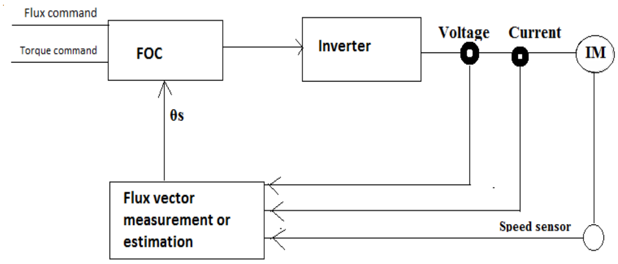

Fig. 2: Direct vector control [14]

ii) Indirect Vector method

In this method, flux angle is not measured directly; instead, it is estimated from the equivalent circuit diagram, measurement of rotor speed, stator current and voltage [14].

Application: Robotics and factory automation.

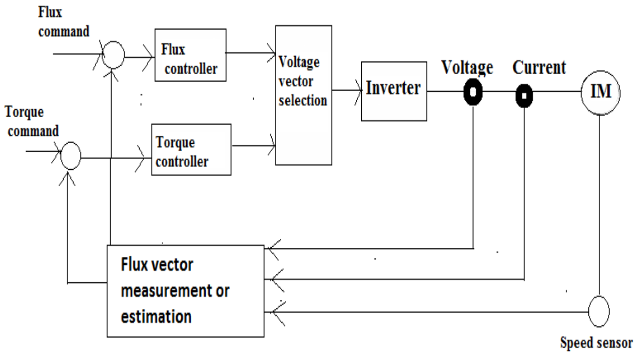

Fig. 3: Indirect vector control [14]

3.3 Direct Torque Control (DTL)

The DTC scheme is no need for d-q transformation. In this case, torque and the stator flux are estimated and directly controlled by applying the appropriate stator voltage vector [15,16].

Advantages:
1. Fastest response time
2. Eliminating the need for a rotor speed sensor
3. Elimination of feedback devices
4. Reduce mechanical failure.

Disadvantages:
1 Inherent hysteresis of the comparator
2. Higher torque
3. Flux ripple exist.

Fig. 4 shows a block diagram of the overall system.

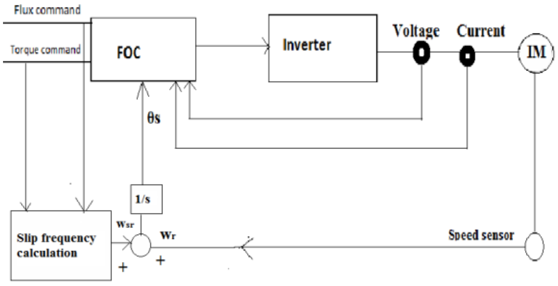

Fig. 4: Direct torque control [14]

Steps followed in DTL:
1. Speed and torque are estimated
2. Estimated speed is compared with the desired value
3. Error signal acts on PI controller to generate reference torque signal.
4. Estimated speed generates a reference signal for the stator flux linkage.
5. Error in torque and stator flux, combined with the angular position of the stator linkage space vector, determines the stator voltage space vector.

Application: Variable speed control.

3.4 Proportional Integral Derivative controller (PID controller)

A PID controller is a feedback control system, which calculates an error value *e*(*t*) as the difference between the reference value and a measured variable and applies a correction based on proportional, integral, and derivative terms continuously [17,18,19]. The controller attempts to minimize the error signal by adjustment of a control variable *u*(*t*) to a new value determined by a weighted sum:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\,dt + K_d \frac{de(t)}{dt}$$

Where K_p, K_i and K_d denote the coefficients for the proportional, integral, and derivative terms respectively [19].

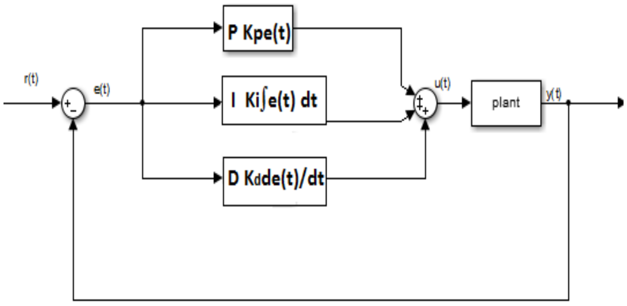

Fig. 5: A block diagram of a PID controller in a feedback loop [17]

In this model,
P - works for present values of the error.
I - works for past values of the error.
D - works for possible future trends of the error.

Increasing the Proportional gain (K_p) will reduce the rise time but never eliminates the steady-state error. Introducing the Integral gain (K_i) will help to reduce the steady state error, but it makes the system very sluggish (and oscillatory), thereby making the transient response very poor. The effect of adding a Derivative gain (K_d) is increase in the stability of the system, reduction in the overshoot, and improvement in the transient response (but no effect on the steady-state error). The general effect of each controller parameter (K_p, K_i, K_d) independently on a closed loop feedback system have been summarized in Table 1.

Table 1: Effects of the parameters K_p, K_i, K_d on closed loop system [19]

Parameter	Rise Time	Overshoot	Settling Time	S-S Error
K_p	Decrease	Increase	Small Change	Decrease
K_i	Decrease	Increase	Increase	Decrease
K_d	Small Change	Decrease	Decrease	No Change

This table should be used for only reference, because this correlation may not be exactly accurate and K_p, K_i & K_d are dependent on each other. In fact, changing one of these variables can change the effect of the other two [19].

3.4.1 PID in Induction Motor Control

Mostly, induction motors are controlled by PI controller [20]. Measured speed is compared with the pre-set value, and the error signal is sent to the PI controller. Based on the error signal, PWM signals are generated and fed to the inverter. From the inverter, enough amount of current and voltage are generated for the correction of speed or torque as shown in Fig. 6. Thus, the desired speed is obtained.

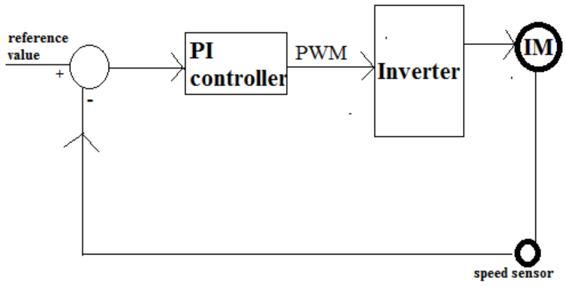

Fig. 6: PI control of Induction Motor

3.5 Sliding Mode Control (SMC)

Sliding mode control is a nonlinear variable control method that a nonlinear system is controlled by a discontinuous control signal. The feedback control law is not a continuous function of time. It can switch from one condition structure to another condition structure according to the current position state. Multiple control laws are designed for a system against different dynamics conditions in order to bring the system in the desired trajectory. The motion of the system, as it slides within the boundaries, is called sliding mode and the surface, where the set of points are defined within the boundaries is called sliding surface [21,22,23].

Advantages:
1. It takes a finite time to reach sliding surface
2. It's Robustness

Applications:
1. Robotics
2. Electric drives

3.5.1 SMC in induction motor control

Sliding mode control is an advanced control method used in many of the applications, like control of induction motor. Here, the trajectory to be followed by the rotor is defined with the control law. A motor can experience different unwanted disturbances, but by ignoring it, the motor must follow the trajectory. Here in Fig. 7, measured speed is compared with the reference; and with this information, fast switching action will be performed in order to bring the motor in the desired condition within a finite time.

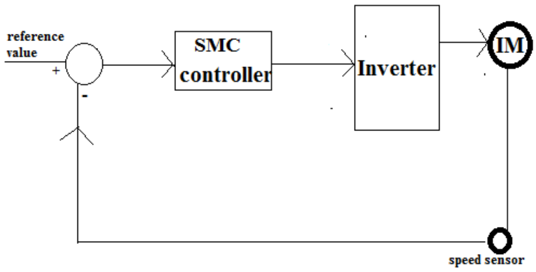

Fig. 7: SMC control of induction motor

4. Comparision of Different Controllers

Table 2 shows the comparision between Scalar and Vector Control. Table 3 shows the comparision between Vector Control and Direct Torque Control (DTC). Table 4 depicts the comparision between PID control and SMC methods. Lastly, Table 5 compares the performances of PID and Sliding Mode Controllers for a change in load at 1.5 sec (after simulation begins), has been shown in Table 5.

Table 2: Comparison between Scalar and Vector Controls [8,24]

Comparison Aspects	**Scalar V/F control**	**Vector control IM**
Speed response	Speed varies at all load conditions	Good speed response with some overshoot
Torque response	In low speed ranges large torques are obtained	Ripples are less
Transient response	Slow	Fast
Difficulty level	Easy	Tough

Table 3: Comparison between Vector Control and Direct Torque Control (DTC) [26]

Comparison Aspects	**Vector Control**	**Direct Torque Control**
Speed Response	Fast and robust	Fastest
Torque response	Faster but spiky	Better torque response
Flux response	Slower and it is affected by the load	Faster and stable
Ease of implementation	Complicated because of the transformation	Easy
V-sag / Interruptions	Speed deviates gradually Current increases gradually	Speed reaches zero at certain points, Current doesn’t increase and it falls suddenly

Table 4: Comparative results of PID and SMC [28]

Controller	%max. overshoot (M_p)	Rise Time (T_r)	Settling Time (T_s)
PI Controller	11.89	38.7 msec	0.8021 sec
Sliding Mode Controller	-	22.2 msec	0.0362 sec

Table 5: Performances of PI and SMC Controllers for a change in load at 1.5 sec after simulation begins [28]

Controller	%drop rotor speed for Load of 10 N-m	%drop rotor speed for Load of 15 N-m
PI Controller	14.11	21.31
Sliding Mode Controller	0.036	0.071

5. Conclusion and Feature Scope

All the controller schemes, which have been mentioned in this paper, have advantages as well as disadvantages according to the area of application. Indeed, the most error-free, more accurate control scheme is preferable. All the conventional methods cannot be forgotten; because of the development of them, it has been possible to come up to this advanced stage. Among the above controlling schemes, newly implemented in most advanced systems is the Sliding Mode Control (SMC). In SMC, there are still problems yet to solve. Finding a new strategy to solve the problems is required. Advanced control design can lead to advanced systems.

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A Review on Different Control Techniques used for Pitch Control of Horizontal Axis Wind Turbine

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Abstract: ***In wind turbine technology, the pitch control mechanism of blades is a very important factor for the efficient power output of a wind turbine. Various control techniques can be implemented for pitch control. This paper deals with the study and review of different control methodologies used by the researchers and engineers to control the pitch angle of the blades of a horizontal axis wind turbine to optimize the power in low rated wind speed. This paper involves the study of PI, PID, Fuzzy logic control, Sliding mode control and Adaptive control methodologies.***

Keywords: Renewable energy, variable Speed Pitch Control, PI, PID, Sliding mode, Fuzzy logic control, Adaptive control

1. Introduction

Due to ever-increasing power demands and the requirements for reduction of carbon emissions, the application of wind energy for electricity production experienced an accelerating growth. There are many technical challenges arises in the integration of wind turbine to the power systems such as reliability, security of supply, availability and power quality. The output electrical power of a wind turbine mainly depends upon the speed of the wind. There are two types of wind turbine, variable speed wind turbine and fixed speed wind turbine. Variable speed wind turbine is preferred over fixed speed wind turbine due to the 10% more power generation as compared to the fixed speed wind turbine. In variable speed wind turbine mainly three control techniques are used to obtain the maximum power output, i.e. pitch control, Yaw control and Power electronic control.

In a variable-speed wind turbine, blade pitch control is very important parameters for efficient energy capture. Different control engineers developed different control strategies for controlling the pitch angle of blades. This paper makes a comparative study of the response of different control techniques used for pitch control. This paper reviews the response of PI, PID, Sliding Mode controller, Fuzzy Logic controller and Adaptive Pitch controller. Due to the different control techniques employed for control the pitch angle, a review study is needed on these recent control techniques used and proposed the best control strategy which gives the desired response and relevant to the nonlinear characteristics of the wind turbine.

2. Evolution of Pitch Control Strategy for Horizontal Axis Wind Turbine

Along with the development of the wind industry, a development in the control of mechanical components, as well as the electrical components, began for maximum power output. Although initially, there were two control concepts proposed for an efficient power output of a wind turbine, i.e., stall control and pitch control, so as to maintain the angle of attack of the blades; however finally, the pitch control concept has been widely accepted due to its adaptability to variable wind speed [3].

The controller for pitch angle can be achieved in two ways, i.e. collective pitch control and Individual pitch control.

In the collective pitch angle, the pitch angle of all the blades is controlled by the same amount [7]. Individual pitch angle control method controls each blade in distinctive manners [8]. In the year of 1999, the researchers presented the pitch control mechanism, where wind turbine operated at an optimum energy level and minimized the load for a wide range of speed [9]. For a wind turbine, implementation of PI controller has been presented by J. G. Slootweg [1] and N. W. Miller *et al*. [2], in 2003. For variable speed wind turbine, a variable pitch angle control using PI controller was presented in the year 2004 by A. D. Hansen *et al.* [4] and by G. Gail *et al.* in 2006 [3]. In the year 2008, Wright A.D and L. J. Fingeresh presented the idea of the non-linear PID pitch control technique [5]. Pitch control using the fuzzy logic controller was presented by J. Zhang in the year 2008 [10]. Implementation of fuzzy logic controllers helps in the improvement of the output power of a wind turbine. It helps to optimize the power at low wind speed and limits the power when the wind speed is high. The sliding mode approach for variable speed wind turbine was presented by H. De Battista *et al*. in 2000 [13] and by B. Beltran *et al*. in 2008 [12]. In high-speed region, using sliding mode approach gives a good power regulation against turbulence and parametric uncertainties. The strategy of adaptive pitch control has been proposed by many researchers, eg., K.E. Johnson and L. Fingersh [14], S. A. Frost *et al*. [15], S. A. Frost *et al*. [16] and S. A. Frost, M. J. Balas and A. D. Wright [17]. This strategy is used when there is a need of a small change of pitch angle under low rated wind speed until the wind turbine reaches its optimum power value. In this paper, we make a comparative study of all these techniques evolved for pitch angle control.

3. Control Strategy

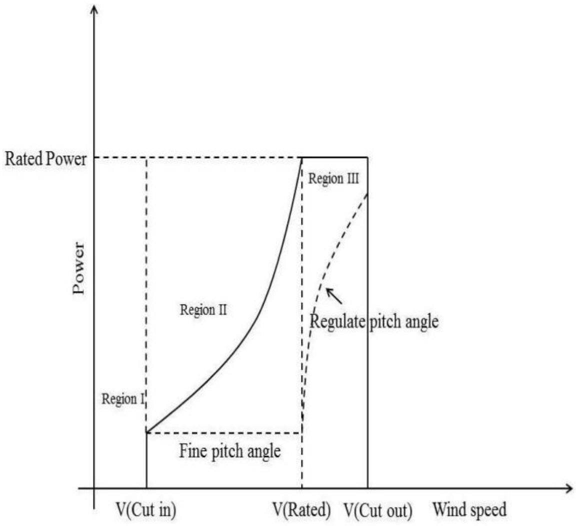

Fig. 1: Power v/s wind characteristics

Fig. 1 shows the relationship between the generated power and wind speed. There are three regions indicated in the characteristics curve. The minimum wind speed required to produce power is called as the cut-in wind speed, wind speed required to produce the rated power is called the rated wind speed and the maximum speed of wind that can be processed for power generation is denoted as cut-out or furling wind speed. In region-1, when the wind speed is lower than V_{cut-in}, the turbine fails to produce any output power. Here in general, pitch angle exclusively remains at 90° due to a less valuable amount of wind speed. Region-2 defined between cut-in (V_{cut-in}) and rated wind speed (V_{rated}) is considered as the operational region where the wind is captured and transformed into valuable power. Region-3 located between rated wind (V_{rated}) and cut-out wind ($V_{cut-out}$) is termed as full load region where a consistent generation of rated-power is realized.

The controller is designed such that in the below-rated region, the turbine's work is to lower power coefficient to increase the wind power for fully exploiting the capacity of the generator. The position of blade pitch angle (β) is kept constant at some fine angle such a way that the wind turbine work remains at its optimal aerodynamic efficiency or power coefficient.

In the above-rated power region, the control strategy is to maintain the rated power constant and reduce the aerodynamic loads of the wind turbine. These two quantities are kept constant by regulating the blade pitch at a different amount of angle.

4. Pitch Controller

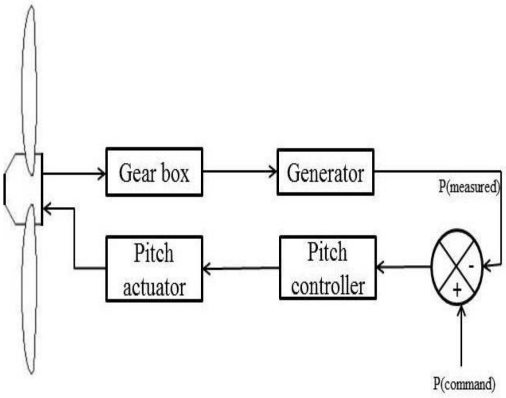

Fig. 2: Control loop for pitch control [25]

The control loop for a pitch controller is shown in Fig. 2. The error signal is generated by the difference between the generated power and given command power value. If the rated power of the wind turbine is known, a command signal can be given to the controller. Pitch control primarily relies on the time constant and rate limiter response of pitch actuator.

5. Different Control Techniques Used In Pitch Control

A) *Proportional, Integral and Differential control*

Proportional Integral (PI) and Proportional Integral and Differential (PID) control techniques are the two most widely used control techniques of pitch control. A proportional controller is used when a slight overspending of the rotor above its nominal value can be allowed and poses no problems for the wind turbine construction. The nonlinear PID pitch control technique for uncertain blade pitch of wind turbine is used for high wind speed.

Fig. 3 shows the response of the pitch angle of PID based pitch actuator system. The system produces a decent response for different values of K_p, K_i and K_d. The gains of the PID controller are chosen according to the methods explained by M. M. Hand [18] and T. Burton *et al.* [19]. There is also another method for selecting the gain of PID pitch control, which is known as symmetric method [6].

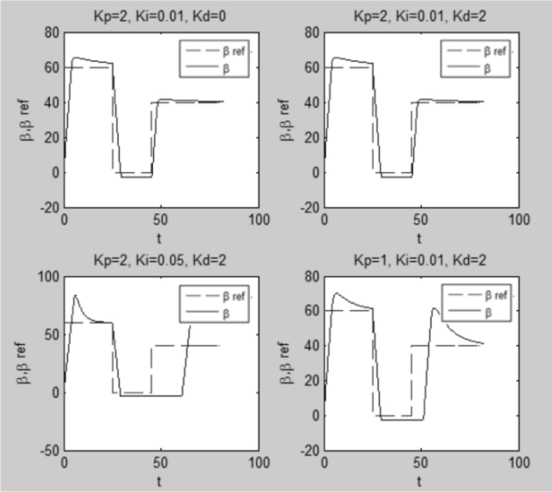

Fig. 3: Pitch-angle response of PID Control based Pitch Actuator System [26]

B) *Sliding Mode Control*

In the case of nonlinear systems having time-varying parameters, sliding mode control technique is used. A discrete control signal is applied to a system in order to push the nonlinearities of the system to slide along a cross-section of the system's normal trajectory [20].

In case of variable speed wind turbine, sliding mode controller is used. This control technique gives output power regulation against turbulence and parametric uncertainties in the high-speed region. One drawback of using this sliding mode control technique is that due to high frequency switching, the trajectory does not follow the sliding path that leads to chattering and a static error occurs [13]. This issue can be minimized by combining SMC with other control methods. Therefore, SMC is integrated with Artificial Neural Network (ANN) controller for best performances.

Table 1 shows the performance comparison of SMC integrated with the ANN controller and PI controller [21], which shows that the average output power using SMC integrated with ANN is more than the PI controller. The speed tracking error and the maximum power tracking error also less in the SMC controller compared to the PI controller.

Table 1: Performance comparison between PI and SMC

Controller	Average power	Max. speed tracking error	Max power tracking error
SMC with ANN controller	805 W	0.67 rad/sec	120 W
PI controller	770 W	1.2 rad/sec	145 W

C) *Fuzzy Logic Control*

The variable-speed wind turbines with blade pitch linear control provide an excellent performance of the closed-loop system. Using fuzzy logic control technique, we can obtain enhanced performance improving the transition between power optimization and power limitation of the wind turbine [23]. Fuzzy logic provides a better performance and it is more robust. It also delivers better mechanical response [22]. Fuzzy logic controller prefers over PI and PID because it can able to process several rule implications simultaneously and produce a complete output.

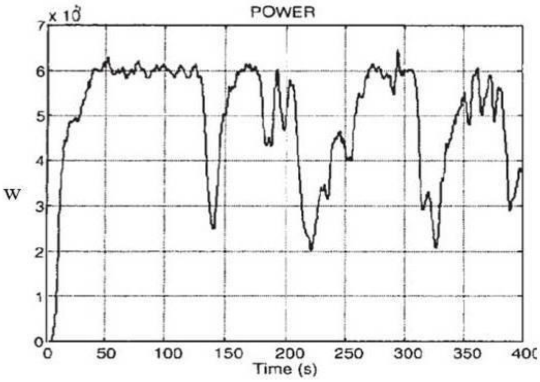

Fig. 4: Generator power for the rated wind time series of the PI control system [23]

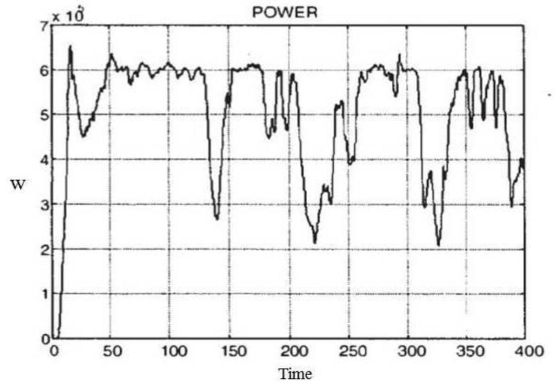

Fig. 5: Generator power for the rated wind-time series of the Fuzzy control system [23].

Table 2: Performance comparison of PI and Fuzzy control

Controller	PI	Fuzzy
Energy(kW)	54.658	55.703
Max. Rotor speed(m/s)	1618	1630

Table 2 shows the performance comparison between the PI controller and the Fuzzy logic controller [23]. By using a fuzzy logic controller, we can get better power output and rotor speed.

D) Adaptive Pitch Control

In the case of below-rated wind speed, it is difficult to identify accurate parameters for the controller. Proper knowledge of power coefficient (C_P) is required to achieve optimal efficiency with a constant gain controller. By using an adaptive control technique, we can overcome the inefficiencies caused by inaccurate knowledge of the C_P [24]. We have to extract maximum possible energy in the below-rated wind speed from a wind turbine. The adaptive pitch controller uses a discrete hill-climbing method to change the blade pitch angle until maximum aerodynamic efficiency is achieved. The discrete time step is known as adoption period number.

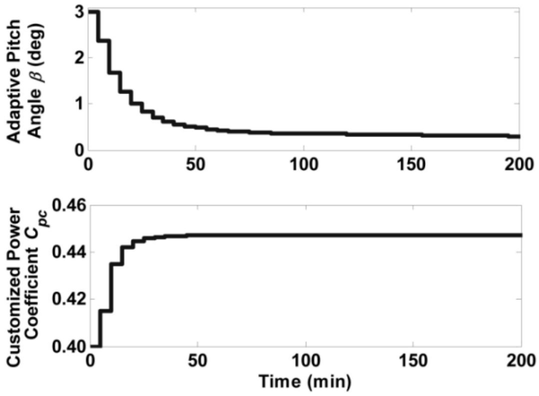

Fig. 6: Simulation Results from constant wind speed adaptive pitch simulation. (Constant wind speed input of 8 m/s and a 5-min. adaptation period.)

The simulation results of adaptive pitch angle and C_{pc} with a constant wind speed of 8 m/s is shown in Fig. 6.The simulation results show that the adaptive pitch angle lies within 3% of the optimal pitch angle of 0.3°. The time is about 200 min and the initial pitch angle is 3°. The adaptation period length is 5 min. As the adaptive pitch angle approaches its optimal value, C_{pc} also approaches $C_{p(max)}$, which equals to 0.447 in this simulation[24].

6. Conclusion

The pitch control of a wind turbine system is reviewed in this paper. This paper mainly deals with the controlling of the pitch angle of a horizontal axis wind turbine in case of varying wind speed. Pitch control is a very important strategy for varying the speed of wind turbines for better speed regulation, which results in maximum power output. Due to the nonlinear behaviour of the moment of inertia of wind turbine, it is a challenging task to implement pitch control mechanism. This study gives some tradeoffs between output response, speed, precision, complexity etc., which helps the researchers to developed new ideas regarding this field.

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