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An approach for improvement of voltage stability condition of a power system using Combination of Power Flow Controllers

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Abstract: This paper presents an approach for using Combination of Power Flow Controllers (COPFC) to improve voltage stability condition (VSC) of a selected bus of a multi-bus power system, which is appeared to be vulnerable to Voltage Instability Problem (VIP). Voltage Stability Index (VSI)-L [1] is used to identify the vulnerable bus of a power system as regards the VSC of the system is represented by the VSI-L of the bus. It is proposed to improve the VSI-L of the vulnerable bus by modifying power flow through a COPFC device available in a transmission line of the power system. For this purpose, sensitivity relations for change in VSI-L of the vulnerable bus and change in power flow through a COPFC device have been derived. Using these sensitivity relations, the power flow of the COPFC is modified to improve the VSC of the vulnerable bus. IEEE 30 and IEEE 118 bus test systems are used to validate the proposed approach.

Keywords: FACTS Device, Voltage Stability, Sensitivity analysis, COPFC device **(Article history: (Received: 31st July 2020 and accepted 15th December 2021)**

I. INTRODUCTION

Open access concept of power system operation under deregulatory environment allows participations of IPPs (Independent Power Producer). To achieve economical objective of system operation under the deregulated environment, it becomes necessary to plan and operate the devices and components of the system at their threshold of operating limit(s). Under such situation, the threat of VIP becomes a major concern for power system planners and operators. Numbers of major blackouts were experienced in many countries [2, 3] due to VIP. VIP is caused due to excessive consumption of power by the system buses. The VIP is indicated by a slow reduction/variation of the voltage magnitude of a bus due to increase in load at the initial part of load increment. Fast reduction in the voltage magnitude is experienced by the system, as it approaches the Proximity of Voltage Collapse (PVC). Several computational based VSIs were proposed [1,4,5,6] to identify the VSC of a power system. For most of these VSIs, their threshold values are provided by the authors to indicate the PVC of the system. In recent years, several algorithms and methods have been developed for on-line monitoring of VIP of a power system using the measurements of bus variable, namely, voltage and current phasors [7-15]. The bus measurements are used for the purpose of representation of Thevenin's equivalent of a power system for selected bus. Therefore, such modeling and analysis is not suitable for deriving measures for improvement of VIP of a multi-bus system.

However, if the issue of voltage stability is not attended properly, it may cause voltage collapse of a power system. Therefore, it is necessary to adopt corrective measure to avoid the possibility of voltage collapse due to VIP of a power system. The corrective measures against VIP of power system are- reactive power scheduling (RPR), generation rescheduling (GR) and load shedding (LS) under emergency condition. Several RPR approaches were suggested for reducing the VIP of a power system [16-21]. Decentralized control architecture is proposed for area wise intelligent agent(s) assignment to monitor the bus voltages and RPR to detect any threat of VIP and related counter measures[22].

The RPR and GR need coordinated efforts of power generation and distribution companies. Further, GR needs time as it is constrained by the ramp-rate of generation unit. Whereas, a Flexible AC Transmission System (FACTS) allows modification of real and reactive power flow(MRRPF) of transmission network. The advances in power electronics technology enables manufacture of fast and reliable FACTS controller, which paves way for utilization of FACTS devices for improvement of performance of power system networks. Load flow analysis is used for operation planning of a power system, in which steady state operational states are determined for the defined power balanced scenario of the system. Several load flow models were proposed for incorporating FACTS device in the load flow analysis. C. R Fuerte-Esqivel and E. Acha presented an algorithm for solution of power flow analysis of a power system containing UPFC device using Newton-Raphson method [23]. UPFC allows control of transmission line real/reactive power flow control and bus voltage/shunt reactive power control [24, 25]. Several works have been reported for improving performance of power system operations involving FACTS device [26-34]. The impact of UPFC controller has been investigated in the area of power system reliability [26,27]. It has been demonstrated that use of UPFC can improve the transient and steady state stability of power system [26-29]. A series FACTS device is used for alleviation of line over load of an overloaded line by rescheduling the power flow through the line containing series FACTS device [30]. An UPFC provides facility for – (i) control of power flow, (ii) secure loading of transmission lines and (iii) quick response time. Therefore, UPFC device could play important role in overcoming VIP of a power system quickly. UPFC device is used for to improve VIP [33-34], where the UFPC was considered in the load bus having problem of voltage instability. In all these works, the traditional UPFC devices were used [34], where the UPFC is represented with series and shunt voltage AC sources.

As such, it seems that UPFC could provide facility to power system planner or operator to change power flow through an UFC device to change network power flow pattern to reduce network congestion and thus create provision for improvement of network voltage profile and VSI of a power system. Such planning needs proper modeling and validation to know the applicability of the UFC device as a corrective measure for improvement of VSI of a power system.

In this paper, a procedure for improvement of VSC of a multi-bus power system has been proposed by re-scheduling the power flow through a COPFC device. Management of reactive power is a key issue to resolve the VIP of a power system. To achieve this objective, a COPFC device is configured with a series flow controller represented with V_s and θ_s and the shunt controller is represented as a variable shunt susceptance (B_{sh}) as, the task of the shunt controller is to provide reactive power support/flow of a COPFC device to manage reactive power support during VIP scenario. The representation of shunt controller with B_{sh}, makes the number of state variables for COPFC device three as compared to conventional modeling of UPFC device with four state variables[35]. This reduces the size of the load flow Jacobian by a row and a column compared to the conventional model of UPFC device. However, a shunt controller of a COPFC has to regulate the current injection through a circuit consisting of Thyristor Switched Capacitor(s) (TSC) and Thyristor Controlled Reactor(s) (TCR). Therefore, it is necessary to determine the number of TSC and injected current through TCR based on reactive power to be controlled by the shunt controller, which is determined by the load flow analysis using for the COPFC model presented in this paper. The VSI –L proposed in reference [1] is utilized to determine the condition of the vulnerable buses of a power system. The VSI-L has a defined scalar threshold value ‘1, which is theoretically established one. The range of this index is 0 to 1, when the value of VSI-L of a power system bus nears 1, one can say that power system is approaching the state of voltage instability zone. Moreover, the representation of VSI-L provides scope for relating power system control variable using NR based load flow model. It is necessary to keep the VSI-L value far below ‘1’ to avoid the possibility of VIP of a system. Therefore, it is proposed to improve the value of VSI-L of the vulnerable bus by modifying power flow and reactive power support of a COPFC device available in a transmission line of the power system. Sensitivity relations for change in VSI-L of the vulnerable bus and change in power flow through a COPFC device have been formulated. These sensitivity relations are utilized to modify power flow and reactive power support of the COPFC device to improve the VSC of the vulnerable bus. Therefore, the proposed method allows improvement of voltage instability condition of a bus of a multi-bus system, which maybe located away from the line containing COPFC device. To implement or introduce COPFC device in a line, a line-tier scheme is adopted with the logic of selecting a line around a selected bus with varying the degree of proximity of the line to the selected bus. This scheme enables investigation of the effectiveness the COPFC device in a line with respect to the degree of proximity of the selected bus while improving its VSI. The passive Inductance has a large size and induces magnetic interference. Due to this, passive inductance is not preferred in electronic systems. Hence there is a need for developing a circuit without the use of inductance or find some alternative to develop it, without core and coil. Thus the alternate way of designing an inductance is the impedance conversion technique.

II. LOAD FLOW ANALYSIS MODEL FOR AN INTERCONNECTED POWER SYSTEM HAVING COPFC DEVICE

A COPFC device is configured as shown in figure-1, where, a series controller of the COPFC device is modeled with a controllable voltage source, having source represented with V_s and θ_s as the state variables.

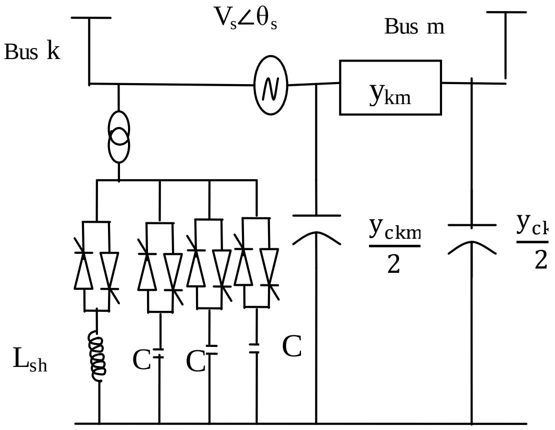

Figure-1 A transmission line between bus-k and bus-m having COPFC device at bus-k.

The task of the shunt controller is to provide RPR of the COPFC device and it consists of capacitor and inductor with provision for reactive power control. The state variable for the shunt controller is represented susceptance (B_{sh}).

The real and reactive power flows through the series controller of the COPFC device can be expressed as [35]:

$$P_{km}=V_k^2 g_{km} - V_k V_m(g_{km}\cos(\delta_{km})+b_{km}\sin(\delta_{km})) - V_k V_s(g_{km}\cos(\delta_k-\theta_s) + (b_{km}+\frac{y_{ckm}}{2})\sin(\delta_k-\theta_s)) \quad (1)$$

$$Q_{km}= -V_k^{2(}(b_{km}+\frac{y_{ckm}}{2}) - V_k V_m(g_{km}\sin(\delta_{km}) - b_{km}\cos(\delta_{km})) - V_k V_s(g_{km}\sin(\delta_k-\theta_s) - (b_{km}+\frac{y_{ckm}}{2})\cos(\delta_k-\theta_s)) \quad (2)$$

$$P_{mk}=V_m^2 g_{km} - V_k V_m(g_{km}\cos(\delta_{mk})+b_{km}\sin(\delta_{mk})) + V_m V_s(g_{km}\cos(\delta_m-\theta_s)+b_{km}\sin(\delta_m-\theta_s)) \quad (3)$$

$$Q_{mk}= -V_m^{2(}b_{km}+\frac{y_{ckm}}{2}) - V_k V_m(g_{km}\sin(\delta_{mk}) - b_{km}\cos(\delta_{mk})) + V_m V_s(g_{km}\sin(\delta_m-\theta_s) + b_{km}\cos(\delta_m-\theta_s)) \quad (4)$$

The basic function of the shunt controller of the COPFC device represented in figure-1 is to regulate current injection through the combination of reactor and capacitors for RPR, according to the required condition. It is convenient to regulate current through an inductor using Thyristor Controlled device, whereas, it is easy to operate capacitors of a COPFC device as Thyristor Switched Capacitor. To explain the process of deriving desired value of B_{sh} for proper RPR based on current control strategy of capacitor(s) and inductor(s), the shunt controller of the device is considered with three TSC and a TCR unit. Using the value of B_{sh} of the conversed load flow analysis for desired RPR of the shunt unit of the COPFC device has to be determined. The expression for reactive power injection of the shunt unit of the COPFC device can be represented as [35]:

$$Q_{ksh}= -V_k^2 B_{sh} \quad (5)$$

Using the value of Q_{ksh}, the number of TSC and injected current of TCR are to be determined for desired operation of the . The reactive power of 'n' number of TSCs and TCR can be represented as:

$$Q_{ksh}= -n\, Q_{kC} + Q_{kL} \quad (6)$$

Where, Q_{kC} and Q_{kL} are the reactive power contributions from a TSC and TCR respectively at kth node of the COPFC . Now, it is necessary to determine the firing angle of the TCR to establish proper RPR of the COPFC devise represented in equation (6). The equation (6) can be rearranged and simplified as follows:

$$Q_{kL} = Q_{ksh} - n\, Q_{kC} = -V_k^2 B_{sh} + nV_k^2 B_{kC}$$

$$\text{i.e., } V_k I_{kL} = nV_k^2 B_{kC} - V_k^2 B_{sh} \quad (7)$$

It is to be noted out that it is necessary determine the number of TSC (n) , so that

$$\left(nV_k^2 B_{kC} - V_k^2 B_{sh}\right) > 0 \quad (8)$$

Equation (7) can be further simplified and related to the firing angle of TCR as given below:

$$I_{kL} = \mathrm{V_k}\ (nB_{kC} - B_{sh}) = \frac{\sqrt{2}V_k}{\pi X_l}(\,1 + cos\alpha)$$
$$i.e,\quad \alpha = \ cos^{-1}[\frac{\pi X_l}{\sqrt{2}}(nB_{kC} - B_{sh}) - 1] \qquad (9)$$

For convenience of formulation, bus number 1 is treated as a slack bus for a multi-bus power system. For a multi-bus power system, Load Flow Jacobian Matrix (LFJM) [J] containing a COPFC device, the NR based load flow model can be represented as [30]:

$$\begin{bmatrix} [\Delta\mathrm{P}] \\ [\Delta\mathrm{Q}] \\ \Delta\mathrm{P_{km}} \\ \Delta\mathrm{Q_{km}} \\ \Delta\mathrm{Q_{ksh}} \end{bmatrix} = [\ \mathrm{J}] \begin{bmatrix} [\Delta\delta] \\ [\Delta\mathrm{V}] \\ \Delta\theta_\mathrm{s} \\ \Delta\mathrm{V_s} \\ \Delta\mathrm{B_{sh}} \end{bmatrix} \qquad (10)$$

Where, $[\Delta\mathrm{V}]^T = [\ V_2 \,..V_n], [\Delta\delta]^T = [\ \delta_2 \,..\,\delta_n], [\Delta\mathrm{P}]^T = [\ P_2 \,..P_n], [\Delta\mathrm{Q}]^T = [\ Q_2 \,..Q_n]$.

III. SENSITIVITY RELATION BETWEEN VSI AND COPFC VARIABLES.

The VSI proposed in reference [1] uses the concept of connectivity of a load to the generation buses of a power system while deriving VSI for a bus. As such, it provides opportunity for deriving a measure for improving VSI of a bus through modification of system state variable. Further, it is possible to relate the system variables to the line flow of the system network elements. The detailed derivation process for relating the VSI of bus to the line flow is provided in this section. The VSI for bus-p of a power system is represented as:

$$L_p = |1 - \textstyle\sum_{i=1}^{N_G} \overline{F_{pi}}\frac{\overline{V_i}}{\overline{V_p}}| \qquad (11)$$

Where, N_G is the number of generation buses. The values of F_{ji} are obtained from the network Y-bus matrix, which is arranged as follows [1]:

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \qquad (12)$$

Where I_G, I_L and V_G, V_L are current and voltage vectors for the generation and load buses. $[Y_{GG}]$, $[Y_{GL}]$, $[Y_{LG}]$, $[Y_{LL}]$ are the network Y-bus matrix. Rearranging equation (12), we obtained [1].

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \qquad (13)$$

Where $[F_{LG}] = [F_{LGR}] + j[F_{LGI}] = -[Y_{LL}]^{-1}[Y_{LG}]$ and element of $[F_{LGR}] + j[F_{LGI}]$ matrix can be represented $F_{ji} < \theta_{ij} = F_{rji} + j\ F_{iji} = |F_{ji}|\cos\theta_{ij} + \mathrm{j}\ |F_{ji}|\sin\theta_{ij}$

Separating, the real and imaginary parts of index L given by equation(11), it can be expressed as:

$$\overline{L_p} = L_{rp} + jL_{ip}$$
$$= 1 - \textstyle\sum_{i=1}^{N_G} F_{pi}\frac{V_i}{V_p}\ [cos(\theta_{pi} + \delta_{ip}) + j\ sin(\theta_{pi} + \delta_{ip})] \qquad (14)$$

Using equation(14), the magnitude index L for bus-p can be expressed as:

$$L_p = \sqrt{(L_{rp})^2 + (L_{ip})^2}$$
$$= \sqrt{\left(1 - \sum_{i=1}^{N_G} F_{pi}\frac{V_i}{V_p} cos(\theta_{pi} + \delta_{ip})\right)^2 + \left(\sum_{i=1}^{N_G} F_{pi}\frac{V_i}{V_p}\ sin(\theta_{pi} + \delta_{ip})\right)^2} \qquad (15)$$

L is an effective VSI, which indicates the condition of a power system with respect to its PVC. It gives a scalar number to each load bus, which varies in the range of 0 to 1. The bus with L-index value near to 1 is the most vulnerable one for PVC. Even for index value around 0.7 to 0.8, the load margin for a bus is significantly low. Hence, slight increase in load in such a bus could lead to voltage collapse of a system. Therefore, it is essential to maintain the VSI for all buses of a power system below a desired value $\mathrm{L_p^{des}}$ (say, 0.4 or less) to overcome PVC in a power system. When the index for a particular bus becomes more than the desired value, corrective measure has to be under taken to bring back the VSI to its desired value. Considering the index, $\mathrm{L_p}$ for a vulnerable bus (bus-p), the desired change in index for bus-p is given as:

$$\Delta\mathrm{L_p^{des}} = \mathrm{L_p^{des}} - \mathrm{L_p} \quad \text{if} \quad \mathrm{L_p} > \mathrm{L_p^{des}} \qquad (16)$$

The change in VSI value $\mathrm{L_p}$ at bus-p vulnerable bus to change system variable vector $[[\Delta\delta]\ [\Delta\mathrm{V}]\ \Delta\theta_s\Delta\mathrm{V_s}\Delta\mathrm{B_{sh}}]$ can be represented as.

$$\Delta\mathrm{L_p} = \left[\frac{\partial L_p}{\partial\delta_2}\cdots\frac{\partial L_p}{\partial\delta_\mathrm{N}}\frac{\partial L_p}{\partial\mathrm{V_2}}\cdots\frac{\partial L_p}{\partial\mathrm{V_N}}\frac{\partial L_p}{\partial\theta_\mathrm{s}}\frac{\partial L_p}{\partial\mathrm{V_s}}\frac{\partial L_p}{\partial\mathrm{B_{sh}}}\right] * \begin{bmatrix} \Delta P_2 \\ . \\ . \\ \Delta P_n \\ \Delta Q_2 \\ . \\ . \\ \Delta Q_n \\ \Delta P_{km} \\ \Delta Q_{km} \\ \Delta Q_{ksh} \end{bmatrix} \qquad (17)$$

Where,

$$\frac{\partial L_p}{\partial \delta_p} = \frac{1}{2L_p}\left[-2L_{rp}\sum_{i=1}^{N_G}\frac{V_i}{V_p}\left(F_{rpi}sin\delta_{ip} + F_{ipi}cos\delta_{ip}\right)\right.$$
$$\left. + 2L_{ip}\sum_{i=1}^{N_G}\frac{V_i}{V_p}\left(-F_{rpi}cos\delta_{ip} + F_{ipi}sin\delta_{ip}\right)\right] \qquad (18)$$

$$\frac{\partial L_p}{\partial \delta_i} = \frac{1}{2\,L_p}[-2\frac{V_i}{V_p}L_{rpi}(sin\delta_{ip} - F_{ipi}cos\delta_{ip})$$
$$+2\frac{V_i}{V_p}L_{ip}F_{rpi}cos\delta_{ip} - F_{ipi}sin\delta_{ip}]\text{for } i=1.N_G \qquad (19)$$

$$\frac{\partial \mathrm{L_p}}{\partial \mathrm{V_p}} = \frac{1}{2\,L_p}\begin{bmatrix} 2L_{rp}\sum_{i=1}^{N_G}\frac{V_i}{V_p^2}\left(F_{rpi}cos\delta_{ik} - F_{ipi}sin\delta_{ik}\right) \\ -2L_{ip}\sum_{i=1}^{N_G}\frac{V_i}{V_p^2}\left(F_{rpi}\,sin\delta_{ip} + F_{ipi}cos\delta_{ip}\right)\end{bmatrix} \qquad (20)$$

$$\frac{\partial L_p}{\partial V_i} = \frac{1}{2\,L_p}[-2L_{rp}\frac{1}{V_p}(F_{rpi}cos\delta_{ik} - F_{ipi}sin\delta_{ip} +$$
$$2L_{ip}\frac{1}{V_p^2}(F_{rpi}sin\,\delta_{ip} + F_{ipi}cos\delta_{ip})\text{For} i= 1.N_G \qquad (21)$$

Substituting $[[\Delta\delta][\Delta V]\Delta\theta_s\Delta V_s\Delta B_{sh}]$ of equation (17) from equation (10), it can be expressed as

$$\Delta L_p = \left[\frac{\partial L_p}{\partial \delta_2}\dots\frac{\partial L_p}{\partial \delta_N}\frac{\partial L_p}{\partial V_2}\dots\frac{\partial L_p}{\partial V_N}\frac{\partial L_p}{\partial \theta_s}\frac{\partial L_p}{\partial V_s}\frac{\partial L_p}{\partial B_{sh}}\right][J]^{-1}\begin{bmatrix}\Delta P_2\\ .\\ .\\ \Delta P_n\\ \Delta Q_2\\ .\\ .\\ \Delta Q_n\\ \Delta P_{km}\\ \Delta Q_{km}\\ \Delta Q_{ksh}\end{bmatrix} \qquad (22)$$

The product of $\left[\frac{\partial L_p}{\partial \delta_2}\dots\frac{\partial L_p}{\partial \delta_N}\frac{\partial L_p}{\partial V_2}\dots\frac{\partial L_p}{\partial V_N}\frac{\partial L_p}{\partial \theta_s}\frac{\partial L_p}{\partial V_s}\frac{\partial L_p}{\partial B_{sh}}\right][\boldsymbol{J}]^{-1}$ provides the sensitivity factors (SFs) that relate the change in bus power injections $[\Delta P]$ and $[\Delta Q]$ along with the change in line power flow ΔP_{km}, ΔQ_{km} and ΔQ_{ksh} as represented below:

$$\Delta L_p = [f_{r2}\dots f_{rN}f_{i2}\dots f_{iN}\alpha_s\beta_s\gamma_{sh}]\begin{bmatrix}\Delta P_2\\ .\\ .\\ \Delta P_n\\ \Delta Q_2\\ .\\ .\\ \Delta Q_N\\ \Delta P_{km}\\ \Delta Q_{km}\\ \Delta Q_{ksh}\end{bmatrix}$$

$$=[[F_r][F_i]\alpha_s\beta_s\gamma_{sh}]\begin{bmatrix}[\Delta P]\\ [\Delta Q]\\ \Delta P_{km}\\ \Delta Q_{km}\\ \Delta Q_{ksh}\end{bmatrix} \qquad (23)$$

Where, $[F_r]$, $[F_i]$ are the SFs which relate change in bus injections $[\Delta P]$, $[\Delta Q]$ and γ_s β_s and γ_{sh} relate the change in COPFC power flow of ΔP_{km}, ΔQ_{km} and ΔQ_{ksh} respectively. It is proposed to improve VSI L_p by changing flow through the COPFC. Therefore, from equation (23), the change in COPFC power flow through the line can be related to change in the VSI of bus-p as follows:

$$\Delta L_p = [\alpha_s \quad \beta_s\gamma_{sh}]\begin{bmatrix}\Delta P_{km}\\ \Delta Q_{km}\\ \Delta Q_{ksh}\end{bmatrix} \qquad (24)$$

Now, multiplying both sides of Eq. (24) by $[\gamma_s \quad \beta_s\gamma_{sh}]^T$, we get:

$$\begin{bmatrix}\alpha_s\\ \beta_s\\ \gamma_{sh}\end{bmatrix}\Delta L_p = [\alpha_s \quad \beta_s\gamma_{sh}]\begin{bmatrix}\alpha_s\\ \beta_s\\ \gamma_{sh}\end{bmatrix}\begin{bmatrix}\Delta P_{km}\\ \Delta Q_{km}\\ \Delta Q_{ksh}\end{bmatrix}$$
$$=[\alpha_s^2 + \beta_s^2 + \gamma_{sh}^2]\begin{bmatrix}\Delta P_{km}\\ \Delta Q_{km}\\ \Delta Q_{ksh}\end{bmatrix} \qquad (25)$$

From equation (25), the required change in COPFC power flow (i.e., ΔP_{km} ,ΔQ_{km} and ΔQ_{ksh}) to change the value of L index by its desired value ΔL_p^{des} can be expressed as:

$$\begin{bmatrix}\Delta P_{km}\\ \Delta Q_{km}\\ \Delta Q_{ksh}\end{bmatrix} = \frac{1}{\alpha_s^2 + \beta_s^2 + \gamma_{sh}^2}\begin{bmatrix}\alpha_s\\ \beta_s\\ \gamma_{sh}\end{bmatrix}\Delta L_p^{des} \qquad (26)$$

The modified COPFC power flow to improve L index by ΔL_p^{des} can be expressed as:

$$P_{km}^{sch(new)} = P_{km}^{sch(old)} + \Delta P_{km} \qquad (27)$$

$$Q_{km}^{sch(new)} = Q_{km}^{sch(old)} + \Delta Q_{km} \qquad (28)$$

$$Q_{ksh}^{sch(new)} = Q_{ksh}^{sch(old)} + \Delta Q_{ksh} \qquad (29)$$

The modified power flow of the line have to be within power transfer limit of the line S_{km}^{max}, i.e.,

$$\sqrt{P_{km}^{sch(new)^2} + Q_{km}^{sch(new)^2}} \le S_{km}^{max} \qquad (30)$$

$$Q_{ksh}^{min} \le Q_{ksh}^{sch(new)} \le Q_{ksh}^{max} \qquad (31)$$

Further it is necessary to satisfy the limits of θ_s and V_s are defined below.

$$-\pi \le \theta_s \le \pi \qquad (32)$$

$$0 \le |V_s \le |0.2|\text{pu} \qquad (33)$$

Further, the relation representation of SFs with COPFC line flow and VSI-L involves linearized LFJM of NR based load flow model, therefore, the SFs offered linear relation between change in COPFC power flow to the change in L_p. As such, the modified COPFC power flow may not establish exact change in ΔL_p^{des}. To overcome this problem, an iterative procedure is adopted, that utilizes a load flow analysis to check L_p after modifying the scheduled flow given by equations (27)-(29) and it checks the condition $|L_p^{des} - L_p| < \varepsilon(= 0.001)$, if this condition is no satisfied iterative procedure is repeated. However, the iterative process needs to be terminated, when operating limits of the COPFC device are violated. Therefore, it is also necessary that the factors α_s β_s $and\, \gamma_{sh}$ are to be sensitive enough to ensure that the operating variables of COPFC device remain within the limits, which is given by equations (30) to (33) while improving L_p. If violation in limits occur, it is not possible to improve L_p using the COPFC device in a line.

IV. RESULTS AND DISCUSSIONS

To validate the proposed approach, the IEEE 30 bus and IEEE 118 bus systems are adopted. To demonstrate the effectiveness of the procedure, VSI of bus 29 of IEEE 30 bus system and VSI of bus 118 of IEEE 118 bus system were pushed above 0.7 and 0.8 respectively by adjusting the system load. Under such loading condition, the base case load flow analysis (BCLFA) for both the systems were carried out and line flows for all the lines were computed for the initial operating condition of the systems.

There is a presumption that in a large power system, the FACTS device has effectiveness on a nearby area of a power system network[30]. It is necessary to carry out investigation to ascertain this presumption in the simulation process. As such, a systematic approach needs to be used to determine degree of proximity of the lines with COPFC device for a selected bus under consideration for VSC and subsequent improvement of VSI of the bus. A network topology processor is utilized for purpose of determining physical proximity of a line with COPFC device for selected bus. The network topology processor is configured for representation of lines connected to selected bus using the concept of line-tier scheme. For this purpose, a data base is created containing a link list for each bus of power system network. This link list possesses the line numbers (with two end bus numbers) of a power system network which are connected to each bus of the system. Using this link list data base, the lines coming under different line-tire level for a selected bus is determined. The line-tier scheme for selected bus is depicted in the figure-2, where lines identified up to three tier level are shown. Therefore, to investigate the use of COPFC device in a transmission line to improve VSI of a selected bus, lines appearing in three line-tier scheme depicted in figure-2 are considered.

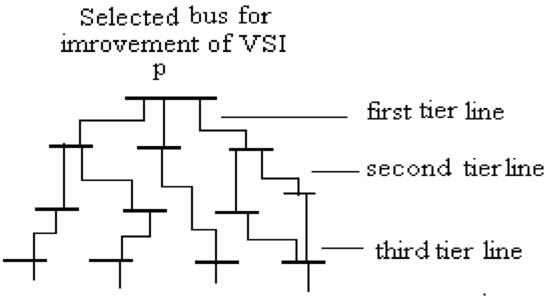

Figure-2: line-tier scheme to select lines for improvement of VSI at bus-p

COPFC device is considered at different transmission lines of the 3-tire scheme one at a time to examine the effectiveness of the proposed method. For all these lines COPFC device is introduces one at a time. The initial scheduled line flows P_{km}^{sch} and Q_{km}^{sch} for the COPFC device is taken as 1.01 times of its line flow through the line determined from BCLFA and Q_{ksh}^{sch} is taken as 0.05 pu.

It is essential to assign proper initial values of θ_s^0 and V_s^0 for numerical stability of a load flow analysis with COPFC device. Therefore, the initial values of θ_s^0 and V_s^0 are determined using the basis given below in reference [23].

$$\theta_s^0 = tan^{-1}\left(\frac{P_{km}^{sch}}{|C_1|}\right) \quad (34)$$

$$V_s^0 = \left(\frac{X_{km}}{V_k^0}\right)\sqrt{{P_{km}^{sch}}^2 + C_1^2} \quad (35)$$

$$C_1 = Q_{km}^{sch} - \frac{X_{km}}{V_s^0}(V_k^0 - V_m^0) \text{if} \quad V_k^0 \neq V_m^0 \quad (36)$$

$$C_1 = Q_{km}^{sch} \text{ if} \quad V_k^0 = V_m^0 \quad (37)$$

A: Simulation results of IEEE 30 bus system: The base case load flow analysis (BCLFA)for IEEE 30 bus system was carried out with defined scheduled power flow for the line appearing in the 3 line-tier scheme with COPFC devise with initial values of Vs and θs given by equations (34)–(37) to determine the initial operating condition of the line and VSI at bus-29. Table-1 present the first load flow analysis results showing COPFC variables and SFs α_s, β_s and γ_{sh}.

Table-1 show that after introduction of COPFC devise in the selected line having scheduled power flow through the COPFC device as 1.01 times of its line flow through the line determined from BCLFA and Q_{ksh}^{sch} as 0.01 pu the VSI at bus-29 changes from its original value of 0.7462.

The procedure provided in section- 3 is used to determine the modified power flow through lines within 3 line-tier scheme to improve VSI at bus-29 to its desired value $L_p^{des} = 0.4$. Table-2 presents the load flow analysis results with COPFC device in selected lines (one at time) showing COPFC power flow, COPFC variables and SFsα_s, β_s and γ_{sh} after improving VSIof bus-29.

Table -2 showed that lines incorporated with COPFC device between the bus-27 and bus-29(line-tier-1), bus-28 and bus-27(line-tier-2) and bus-6 and bus-28 (line-tier-3) could reduce the VSI to its set desired value. Other lines in the 3 line-tier system could not reduce the value of VSI at bus 29 to the desired value because of violation of series controller voltage limit of COPFC device, except the lines between bus-28 and bus-8

TABLE-1: First load flow analysis results of IEEE 30 bus system showing COPFC variables and SFsα_s, β_s and γ_{sh} for the lines with COPFC device considered for improvement of VSI

VSI of bus-p determined by BCLFA	Two end bus number of line considered for introducing COPFC		Tier level	Line flow through the line considered for VSI improvement	COPFC variables $P_{km} = 1.01\,P_{km}^0$, $Q_{km} = 1.01\,Q_{km}^0$ and $Q_{ksh} = 0.01$			VSI at bus-29 after introduction of COPFC in the line connected between bus-k and bus-m
VSI value at bus-29 $L_{29} = 0.7462$	k	m		P_{km}^o Q_{km}^o	$P_{km} = 1.01\,P_{km}^0$ $Q_{km} = 1.01\,Q_{km}^0$ $Q_{ksh} = 0.01$	V_s in pu θ_s in radian B_{sh} in pu	α_s B_s γ_{sh}	L_{29}
	27	29	1	0.2231 0.1329	0.2253 0.1342 0.0100	0.0098 3.0520 -0.0155	-6.3752 -7.5094 4.9560	0.7351
	30	29	1	-0.0353 -0.0190	-0.0357 -0.0192 0.0100	0.0109 2.1857 -0.0154	-0.7989 -0.1583 3.9366	0.7839
	27	25	2	0.1010 0.0632	0.1020 0.0638 0.0100	0.0218 3.0333 -0.0160	1.9057 4.5934 4.7964	0.7965
	30	27	2	-0.1607 -0.0700	-0.1623 -0.0707 0.0100	0.0151 1.6432 -0.0155	4.2857 3.3107 5.9146	0.7942
	28	27	2	0.4823 0.3816	0.4872 0.3854 0.0100	0.0097 -0.6653 -0.0114	2.1193 5.1294 0.0621	0.7818
	24	25	3	0.0535 0.0603	0.0540 0.0609 0.0100	0.0078 -0.3192 -0.0153	-2.9956 -6.1204 -0.1075	0.7392
	25	26	3	0.1502 0.1157	0.1517 0.1169 0.0100	0.0036 -0.8875 0.0170	1.0142 1.5767 1.5767	0.7662
	28	8	3	-0.1406 -0.2561	-0.1420 -0.2586 0.0100	0.0005 1.3395 -0.0113	0.1823 0.3493 0.3492	0.7487
	6	28	3	0.3711 0.2713	0.3748 0.2740 0.0100	0.0016 2.8677 -0.0108	-0.4277 -0.7626 0.0389	0.6482

TABLE-2: COPFC scheduled power flow, variables and SFsα_s, β_s and γ_{sh} for the lines after improvement of VSI to its desired value at bus-29 of IEEE 30 bus system

VSI of bus-p determined by BCLFA	VSI value of bus-p value after introducing the COPFC device.	Two end bus number of line considered for introducing COPFC		Tier level	COPFC scheduled power flow, variables and SFs α_{pq}, β_{pq}			VSI at bus-29 after improvement
		k	m		P_{km} Q_{km} Q_{ksh}	V_s in pu θ_s in radian B_{sh} in pu	α_s B_s γ_{sh}	
VSI value at bus-29 $L_{29} = 0.7462$	0.7351	27	29	1	0.2553 0.1611 0.0030	0.1697 2.9962 -0.0042	-0.0042 -3.2263 0.5768	0.4006
	0.7839	30	29	1	0.0391 0.0095 -0.1009*	0.1657 -2.6420 0.1809	-0.9345 -0.2910 0.7685	0.4896
	0.7965	27	25	2	0.0775 0.0127 -0.0437	0.2143* -0.1914 0.0546	0.7454 1.2667 1.3576	0.5078
	0.7942	30	27	2	-0.2412 -0.1118 -0.0738	0.2037* -0.2389 0.0882	1.0382 0.3281 0.8119	0.4293
	0.7818	28	27	2	0.4823 0.3713 0.0099	0.1558 2.9824 -0.0111	-3.8212 -6.0235 -0.1206	0.4006
	0.7392	24	25	3	0.0848 0.1164 0.0120	0.2014* 2.9781 -0.0198	-1.3058 -1.9868 -0.1412	0.4880
	0.7662	25	26	3	0.1245 0.0758 -0.0310	0.2007* 3.1355 0.0458	0.6726 0.9236 0.9236	0.6361
	0.7487	28	8	3	-0.2039 -0.3703 -0.1016*	0.0486 -0.0676 0.1099	0.1499 0.2536 0.2535	0.6661
	0.6482	6	28	3	0.7445 0.7949 -0.0120	0.1990 3.0025 0.0132	-0.2202 -0.2369 0.0069	0.4006

* indicates the limit violation of COPFC variables.

bus-30 and bus-29, where, the reactive power limit (set as $Q_{ksh}^{min} = -0.1$ pu and Q_{ksh}^{max} =0.1 pu) of shunt controller were violated. Table-1 and table-2 indicated that the SFsα_s, β_s and γ_{sh} change in the iterative process as was explained in section-3. Further, it is observed from the simulation on IEEE 30 bus system that line having COPFC device at 3rdline-tier level is also effective in reducing the value of VSI at a selected bus.

B: Simulation results of IEEE 118 bus system: The base case load flow analysis (BCLFA) for IEEE 118 bus system was carried out with defined scheduled power flow for the line appearing in the 3 line-tier scheme with COPFC device with initial values of Vs and θs given by equations (34) – (37) to determine the initial operating condition of the line and VSI at bus-118. Table-5 present the first load flow analysis results showing COPFC variables and SFsα_s, β_s and γ_{sh}.

The procedure provided in section- 3 is used to determine the modified power flow through lines within 3 line-tier scheme to improve VSI at bus-118 to its desired value $L_p^{des} = 0.5$. Table-3 presents the load flow analysis results with COPFC device in selected lines (one at time) showing COPFC power flow, COPFC variables and SFsα_s, β_s and γ_{sh} after improving VSI of bus-118.

Table -3 showed that lines incorporated with COPFC devices for lines appearing in the third line-tier scheme for IEEE 118 bus system, where, the reactive power limit (set as $Q_{ksh}^{min} = -0.4$ pu and Q_{ksh}^{max}=0.4 pu) of shunt controller were violated. Table-3 and table-4 indicated that the SFsα_s, β_s and γ_{sh} change in the iterative process, which is observed in case of IEEE 30 bus system also. Again, it is observed from the simulation on IEEE 118 bus system that line having COPFC device at 3rdline-tier level is also effective in reducing the value of VSI at a selected bus. However, some of the lines appearing in the 3rd line-tier scheme found to be less effective in reducing VSI for the selected 118 bus system. Therefore, results for only a few 3rdline-tier lines are presented in table 3 and table 4.

Again, use of line-tier scheme for considering COPFC device in transmission line simplifies the section process for introduction of COPFC device in a line. Because, this scheme helps in selecting line for introduction of a COPFC device, those are around different degree of proximity to a bus under consideration and also study the variation of SFs for the lines at different line-tier scheme.

Simulation results for IEEE 30 and IEEE 118 bus systems showed that it would be possible to improve VSI of a selected bus by modifying power flows through a transmission line having COPFC device located anywhere in the system, provided that it is sensitive enough to the selected bus. It is due to the fact that the of power flow pattern of a power system network is changed to reduce network congestion and this results in improvement of voltage profile of the network buses and finally improves VSI of a power system.

V. CONCLUSION

This paper presented a procedure for improving VSI of a power system bus by re-scheduling power flow (both real and reactive power) and RPR of a COPFC device. To achieve this objective, a COPFC device is configured with a series controller represented with state variable $V_s$and θ_s and the shunt controller is represented as a variable shunt susceptance (B_{sh}). This configuration allows independent control of both real and reactive power control of the series controller and reactive power control of shunt controller. The VSI proposed in reference [1] is utilized to identify the bus(es) vulnerable to VIP of bus. VSI of vulnerable bus is improved by modifying power flow and reactive power support of a COPFC device available in a transmission line of the power system. To determine the modified power flow of the COPFC device, the SFs for change in VSI-L of the vulnerable bus and change in power flow through a COPFC device have been derived. These SFs are utilized to modify power flow and reactive power support of the COPFC device to improve the VSC of the vulnerable bus.

Another important study carried out in this work is to examine the effect COPFC device on VSI of bus located around the selected bus varying degree of proximity. For this purpose, a line-tier scheme has been develop and investigation has been carried out up to three tier level. This line-tier scheme for considering COPFC device in transmission line simplifies the section process for introduction of COPFC device in a line. Because, this scheme helps in selecting line for introduction of a COPFC device, those are around different degree of proximity to a bus.

TABLE-3: First load flow analysis results of IEEE 118 bus system showing COPFC variables and SFs α_s, β_s and γ_{sh} for the lines with COPFC device considered for improvement of VSI .

VSI of bus-p determined by BCLFA	Two end bus number of line considered for introducing COPFC		Tier level	Line flow through the line considered for VSI improvement	COPFC variables $P_{km} = 1.01\, P_{km}^0$, $Q_{km} = 1.01\, Q_{km}^0$ and $Q_{ksh} = 0.01$			VSI at bus-118 after introduction of COPFC in the line connected between bus-k and bus-m L_{118}
VSI value at bus-118	k	m		P_{km}^o Q_{km}^o	$P_{km} = 1.01\, P_{km}^0$	V_s in pu θ_s in radian	α_s B_s γ_{sh}	

$L_{118} =$ 0.8027					Q_{km} $= 1.01\ Q^0_{km}$ $Q_{ksh} = 0.01$	B_{sh} in pu		
	75	118	1	2.2474 2.1205	2.2699 2.1417 0.010	0.0045 -0.5326 -0.0164	0.3660 0.6798 0.1634	0.8330
	118	76	1	-0.6159 -0.3700	0.6220 -0.3737 0.0100	0.0038 0.5691 -0.0262	0.7300 0.8774 0.9344	0.8048
	69	75	2	2.4055 1.6149	2.4295 1.6311 0.0100	0.0131 -2.7929 -0.0092	-0.3232 -0.9241 0.0000	0.7018
	75	70	2	-0.2264 -0.6557	-0.2287 -0.6623 0.0100	0.0013 -0.0453 -0.0163	0.1874 0.3152 0.4004	0.8045
	75	74	2	0.3224 -0.3801	0.3256 -0.3839 0.0100	0.0012 -1.8206 -0.0163	0.1423 0.2561 0.3700	0.8065
	75	77	2	-0.7315 -0.4367	-0.7388 -0.4411 0.0100	0.0029 0.7687 -0.0163	0.2133 0.3282 0.3897	0.8038
	76	77	2	-1.3173 -0.7967	-1.3305 -0.8046 0.0100	0.0071 0.8335 -0.0223	0.6149 0.8668 0.9094	0.7956
	80	77	3	2.0569 1.8290	2.0774 1.8473 0.0100	0.0023 -2.6631 -0.0092	-0.0589 -0.1427 0.0000	0.7980
	74	70	3	-0.3624 -0.5836	-0.3660 -0.5894 0.0100	0.0014 0.4750 -0.0157	0.1941 0.2832 0.3713	0.8044
	71	70	3	-0.4309 1.1349	-0.4352 1.1463 0.0100	0.0039 1.9672 -0.0111	-0.0412 -0.2029 -0.0076	0.7998
	78	77	3	-0.2978 0.2812	-0.3008 0.2840 0.0100	0.0015 2.5967 -0.0108	-0.0326 -0.0781 -0.0017	0.8025

Table-4: COPFC scheduled power flow, variables and SFsα_s, β_s and γ_{sh} for the lines after improvement of VSI to its desired value at bus-118 of IEEE 118 bus system

VSI of bus-p determined by BCLFA	Two end bus number of line considered for introducing COPFC		Tier level	Line flow through the line considered for VSI improvement	COPFC scheduled power flow, variables and SFsα_{pq}, β_{pq}			VSI at bus-118 after improvement
VSI value at bus-118 $L_{118} =$ 0.8027	k	m		P^o_{km} Q^o_{km}	P_{km} $= 1.01\ P^0_{km}$ Q_{km} $= 1.01\ Q^0_{km}$ $Q_{ksh} = 0.01$	V_s in pu θ_s in radian B_{sh} in pu	α_s B_s γ_{sh}	
	75	118	1	2.2474 2.1205	2.1285 1.8869 -0.0467	0.0808 3.1377 0.0701	0.6148 1.0378 0.2091	0.5008
	118	76	1	-0.6159 -0.3700	0.8152 -0.5741	0.1803 0.0083	0.2589 0.2290	0.5006

					-0.2043	0.3617	0.2461	
	69	75	2	2.4055 1.6149	2.6390 2.1260 0.0100	0.1873 -2.9724 -0.0092	-0.1083 -0.2172 -0.0000	0.5007
	75	70	2	-0.2264 -0.6557	-0.4751 -1.0210 -0.4457	0.1448 0.0278 0.5959	0.0904 0.1116 0.1419	0.5680
	75	74	2	0.3224 -0.3801	0.1512 -0.6629 -0.3979	0.1478 0.0340 0.5557	0.0800 0.1081 0.1618	0.5889
	75	77	2	-0.7315 -0.4367	-1.0012 -0.8002 -0.4179	0.1714 0.0027 0.5537	0.0972 0.1155 0.1383	0.5674
	76	77	2	-1.3173 -0.7967	-1.5249 -1.0227 -0.2196	0.1427 -0.1630 0.3223	0.2319 0.2105 0.2225	0.5006
	80	77	3	2.0569 1.8290	3.2455 4.2011 0.0100	0.2026 -3.0047 -0.0092	-0.0299 -0.0497 -0.0000	0.5162
	74	70	3	-0.3624 -0.5836	-0.6245 -0.9215 -0.4288	0.1565 -0.0087 0.5196	0.0912 0.0999 0.1334	0.5888
	71	70	3	-0.4309 1.1349	-0.1245 2.1774 0.0683	0.2269 -2.8005 -0.0842	-0.0425 -0.0993 -0.0091	0.6128
	78	77	3	-0.2978 0.2812	0.2029 1.4654 0.0924	0.2600 3.1306 -0.1572	-0.0359 -0.0813 -0.0231	0.6726

under consideration and also study the variation of SFs for the lines at different line-tier scheme.

Further, simulation analysis showed that the proposed method allows improvement of VSC of a bus of a multi-bus system for a COPFC device located even at third tier level of the line-tier scheme. Therefore, SFs used to determine the modified reschedule power flow through the COPFC device to improve the VSI L_p of the bus to a desired value may be more sensitive for the lines located at higher range line-tier scheme. Simulation results for IEEE 30 and IEEE 118 bus systems showed that it would be possible to improve VSI of a selected bus by modifying power flows through a transmission line having COPFC device located anywhere in the system. But, it is important that the SFs α_{s}, β_s and γ_{sh} of a COPFC device are to be sensitive enough to improvement of the VSC of the selected bus rather than the proximity of the COPFC device to the selected bus.

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