Journal of Multidisciplinary Engineering Science and Technology (JMEST)
ISSN: 2458-9403
Vol. 7 Issue 5, May - 2020

POWER FLOW ANALYSIS USING INTERLINE POWER FLOW CONTROLLER

Eti-Ini Robson Akpan[1],
Department of Electrical/Electronic and Computer Engineering, University of Uyo, Akwa Ibom, Nigeria

Ozuomba Simeon[2]
Department of Electrical/Electronic & Computer Engineering, University of Uyo, Akwa Ibom, Nigeria
simeonoz@yahoomail.com
simeonozuomba@uniuyo.edu.ng

Sam BasseyAsuquo [3]
Department of Electrical/Electronic & Computer Engineering, University of Uyo, Akwa Ibom, Nigeria

***Abstract*— This paper presented power flow analysis using Interline Power Flow Controller (IPFC) , a case study of Afam-Alaoji, Sapele-Benin, Sapele-Aladja, Delta-Aladja and Delta-Benin transmission lines in Nigeria. It is aimed at minimizing high power losses and normalizing voltages in the transmission lines. The IPFC device was inserted in the first and the second buses (Afam and Alaoji). The buses and lines data were the input along with the IPFC parameters which were used to obtain the Jacobian Matrix and to determine the power mismatches in the transmission lines. The power flow analysis was conducted using the Newton-Raphson algorithm which was simulated in MATLAB program. The simulation was conducted with and without the IPFC. The results showed that the total real and reactive power losses obtained when the power flow simulation was done without and with IPFC were 245.90 MW and 217.25 MVar (without the IPFC) and 186.28 MW and 38.163 MVar (with the IPFC) respectively. The use of IPFC improved the voltage profile by 90%. Hence, the study shows that the IPFC was effective in optimizing power losses and normalizing the voltages in the cases study transmission lines. However, further works is required for the determination of the optimal location of the IPFC in the transmission lines.**

Keywords*— *Interline Power Flow Controller (IPFC), Power Flow Analysis, Power Losses, Transmission Lines, Jacobian Matrix, Power Mismatches, Newton-Raphson Algorithm

I. INTRODUCTION

The evolution of power industry in recent years has imposed many challenges due to the radical changes in the energy market as power demand, in many cases, is more than the available power. Due to the heavy demand for power, distribution networks are always stressed which results in reduced voltage across the load and this affects the performance of the power system [1,2,3]. It is therefore necessary to improve the performance of the power system in order to deliver acceptable quality power at the consumer end.

Notably, the reactive power compensation is the main measure to keep power network running with high voltage stability, high power quality and minimum system loss [4,5,6,7,8]. Also, over the years, the flexible alternating current transmission system (FACTS) devices have been found to be very effective controller for enhancing the power system performance [9,10,11,12,13,14]. The FACTS controllers use thyristor-switched-capacitors or reactors to provide reactive shunt and series compensation [15,16,17,18,19,20]. FACTS controllers are broadly classified as series or shunt, and both categories are used to modify the natural electrical characteristics of ac power system. The series compensation modifies the transmission or distribution system parameters, while the shunt compensation changes the equivalent impedance of the load. In both cases, the reactive power that flows through the system can be effectively controlled by FACTS, which improves the overall performance of ac power system.

Furthermore, presently, there is a number of FACTS device controllers, the shunt controller like static VAR compensator (SVC) [21,22], the static synchronous compensator (STATCOM) [23,24], the series controller like thyristor controlled series capacitor (TCSC) [25,26] and the static synchronous series compensator (SSSC) [27,28]. There is a third classification which is a combination of both series and shunt controllers like thyristor-controlled phase shift transformer (TCPST), interline power flow controller (IPFC), unified power flow controller (UFPC) and dynamic flow controller (DFC) [29,30]. The IPFC is among the FACTS devices aimed at simultaneously providing dynamic compensation and effective power flow management in transmission lines [31,32,33]. Therefore, the main objective of this paper is to use IPFC to minimize power losses in a transmission line. The study is based on data collected from a case study 330kV transmission line in Nigeria. In the study, the IPFC controller is modeled and used along with the Newton-Raphson power flow method to determine the voltage profile of the generator and the load buses with and without using the IPFC. Finally, the models are simulated and the performance of the IPFC model is also determined using a program written in the matrix laboratory (MATLAB) software.

II. METHODOLOGY

The power injection model for the interline power flow controller (IPFC) is derived based on the equivalent circuit of IPFC shown in Figure 1.

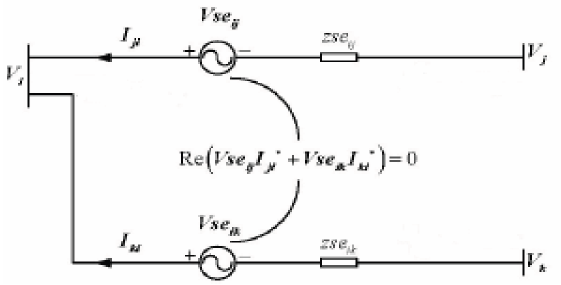

Figure 1 Equivalent circuit of two converter IPFC [34,35]

In Figure 1, V_i, V_j and V_k are the complex bus voltages at the buses i, j and k respectively, and they are defined as;

$$V_x = V_x \angle\theta_x \quad for\ x = i, jand\ k \qquad (1)$$

Where Vse_{in} is the controllable series injected voltage source, defined as;

$$Vse_{in} = Vse_{in} < \theta se_{in}\ (n = j, k) \qquad (2)$$

Where $Zse_{in}\ (n = j, k)$ is the series coupling transformer impedance.

The active and reactive power injections at each bus is determined as follows [34,35];

$$P_{inj,i} = \sum_{n=j,k} V_i Vse_{in} b_{in} \sin(\theta_i - \theta se_{in}) \qquad (3)$$

$$Q_{inj,i} = -\sum_{n=j,k} V_i Vse_{in} b_{in} \cos(\theta_i - \theta se_{in}) \qquad (4)$$

$$P_{inj,n} = -V_n Vse_{in} b_{in} \sin(\theta_n - \theta se_{in}) \qquad (5)$$

$$Q_{inj,n} = V_n Vse_{in} b_{in} \sin(\theta_n - \theta se_{in}) \qquad (6)$$

Where n = j,k

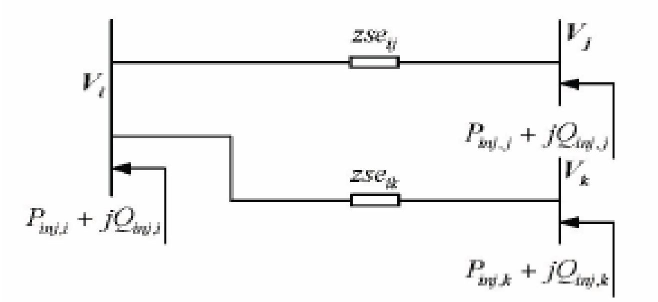

Figure 2: Power injection model of two converter IPFC
(Source :[34]

The equivalent power injection model of an IPFC is shown in Figure 2. The active and reactive power flow control constraints are given as[34,35];

$$P_{ni} - P_{ni}^{spec} = 0 \qquad (7)$$

$$Q_{ni} - Q_{ni}^{spec} = 0 \qquad (8)$$

Where *n=j,k and* P_{ni}^{spec} and Q_{ni}^{spec} are the specified active and reactive power flow control references respectively, which are given as;

$$P_{ni} = Re\,(V_n I_{ni}^{*}) \qquad (9)$$

$$Q_{ni} = Re\,(V_n I_{ni}^{*}) \qquad (10)$$

The power balance equations are as follows [34,35];

$$P_{gm} + P_{inj,m} - P_{lm} - P_{line,m} = 0 \qquad (11)$$

$$Q_{gm} + Q_{inj,m} - Q_{lm} - Q_{line,m} = 0 \qquad (12)$$

The IPFC model used is given as follows [34,35];

$$P_{inj,i} = \sum_{n=j,k} V_i Vse_{in} b_{in} sin(\theta_i - \theta se_{in}) \qquad (13)$$

$$Q_{inj,i} = -\sum_{n=j,k} V_i Vse_{in} b_{in} \cos(\theta_i - \theta se_{in}) \qquad (14)$$

$$P_{inj,n} = -V_n Vse_{in} b_{in} \sin(\theta_n - \theta se_{in}) \qquad (15)$$

$$Q_{inj,n} = V_n Vse_{in} b_{in} \sin(\theta_n - \theta se_{in}) \qquad (16)$$

Where n = j,k

$$P_{gm} + P_{inj,m} - P_{lm} - P_{line,m} = 0 \qquad (17)$$

$$Q_{gm} + Q_{inj,m} - Q_{lm} - Q_{line,m} = 0 \qquad (18)$$

where Pgm and Qgm are the generator active and reactive powers, Plm are load active and reactive powers, Pline ,m and Qline,m are conventional transmitted active and reactive powers. The load flow equations for the PQ busbar are given as;

$$\Delta P_i = P_i^{sp} - V_i \sum_{k=1}^{n} V_k \left(G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik}\right) \qquad (19)$$

$$\Delta Q_i = Q_i^{sp} - V_i \sum_{k=1}^{n} V_k \left(G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik}\right) \qquad (20)$$

Where ΔP_i *and* ΔQ_i are called the active and reactive power mismatches at busbar*i.*

The Jacobian matrix used in the Newton Raphson iterative solution in Figure 3 is given as;

$$0 = \begin{bmatrix} \Delta P^p \\ \cdots \\ \Delta Q^p \end{bmatrix} - \begin{bmatrix} \underline{H}^p & \vdots & \underline{N}^p \\ \cdots & \cdots & \cdots \\ \underline{J}^p & \vdots & \underline{L}^p \end{bmatrix} \begin{bmatrix} \Delta\theta^p \\ \cdots \\ \frac{\Delta V^p}{V^p} \end{bmatrix} \qquad (21)$$

Where $\Delta \underline{P}^p$ are the real power mismatches at all *PQ* and *PV* buses, $\Delta \underline{Q}^p$are the reactive power mismatches at all *PQ* buses, $\Delta\underline{\theta}^p$are the θ corrections for all *PQ* and *PV* buses, and $\frac{\Delta V^p}{V^p}$provide the *V* corrections for all *PQ* buses. The division of each ΔV_i^p by V_i^p does not numerically affect the algorithm, but simplifies some of the Jacobian matrix terms. For busbars *i* and *k* (not row *i* and column *k* in the matrix), the following expressions applies;

$$H_{ik} = -\frac{\partial \Delta P_i}{\partial \theta_k} \qquad (22)$$

$$N_{ik} = -V_k \frac{\partial \Delta P_i}{\partial V_k} \qquad (23)$$

$$J_{ik} = -\frac{\partial \Delta Q_i}{\partial \theta_k} \qquad (24)$$

$$H_{ik} = -V_k \frac{\partial \Delta Q_i}{\partial V_k} \qquad (25)$$

$$0 = \begin{bmatrix} \Delta P_1 \\ \Delta P_3 \\ \Delta P_4 \\ \cdots \\ \Delta Q_1 \\ \Delta Q_4 \end{bmatrix} - \begin{bmatrix} H_{11} & 0 & H_{14} & \vdots & N_{11} & N_{14} \\ 0 & H_{34} & N_{34} & \vdots & 0 & N_{34} \\ H_{41} & H_{43} & H_{44} & \vdots & N_{41} & N_{44} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ J_{11} & 0 & J_{14} & \vdots & L_{11} & L_{14} \\ J_{41} & J_{43} & J_{44} & \vdots & L_{41} & L_{44} \end{bmatrix} \begin{bmatrix} \Delta\theta_1 \\ \Delta\theta_3 \\ \Delta\theta_4 \\ \cdots \\ \Delta V_1/V_1 \\ \Delta V_4/V_4 \end{bmatrix} \qquad (26)$$

The expressions for the calculation of the elements of $\underline{H}$, $\underline{N}$, $\underline{J}$, and $\underline{L}$ are obtained by partial differentiation and the expressions are as follows;

$$H_{ik} = L_{ik} = V_i V_k (G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik}) i \neq k \qquad (27)$$

$$H_{ik} = -J_{ik} = V_i V_k (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik}) i \neq k \qquad (28)$$

$$H_{ii} = -B_{ii} V_i^2 - Q_i \qquad (29)$$

$$N_{ii} = G_{ii} V_i^2 + P_i \qquad (30)$$

$$J_{ii} = -G_{ii} V_i^2 + P_i \qquad (31)$$

$$L_{ii} = -B_{ii} V_i^2 + Q_i \qquad (32)$$

Where P_i and Q_i are the calculated net busbar active and reactive powers given by the summation terms in Equation (19) and Equation (20). The flowchart for Newton-Raphson method with IPFC model is given in Figure 3.

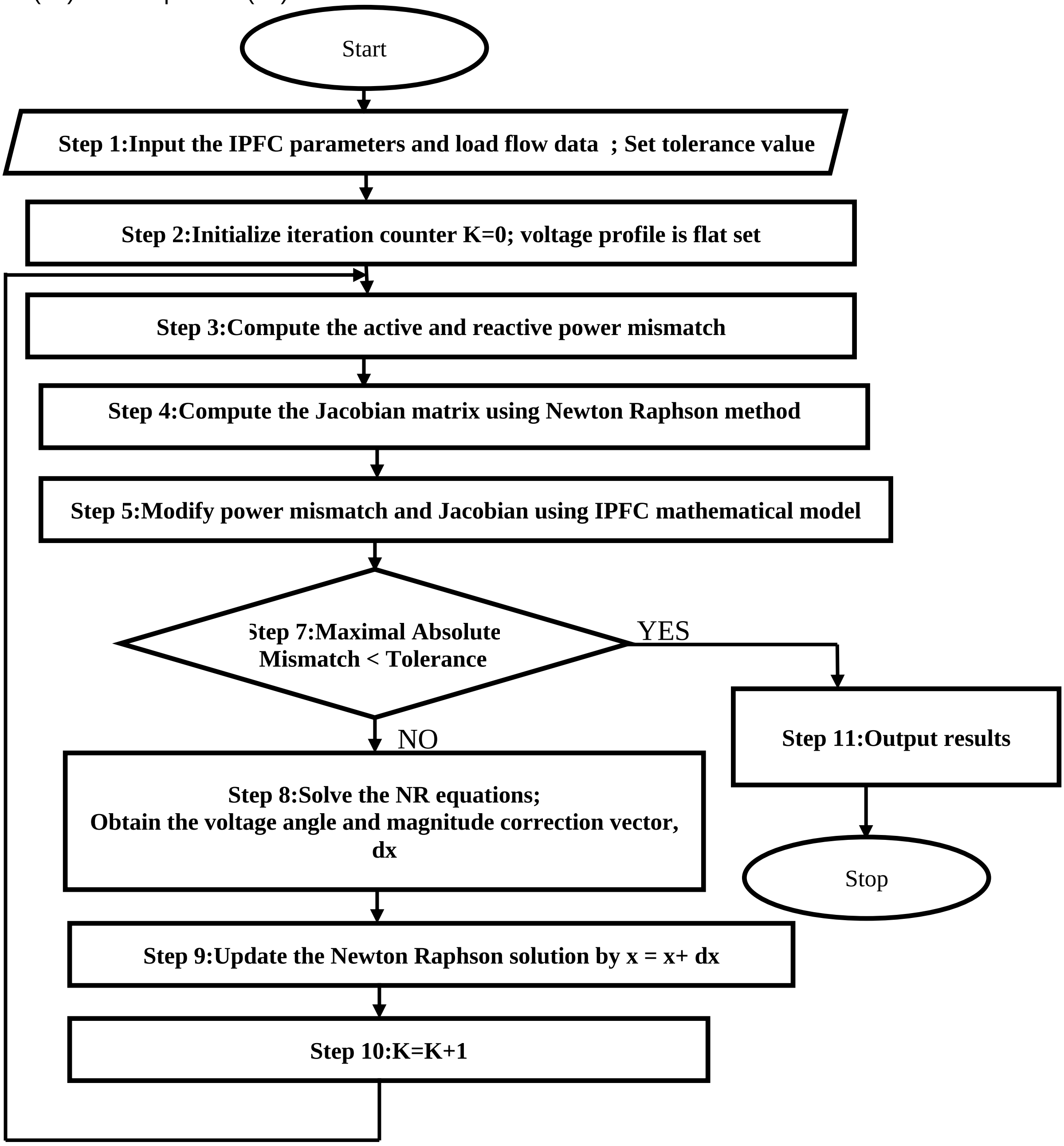

Figure 3 The flowchart for Newton-Raphson method with IPFC model

The case study is the existing Nigerian South-South 330 KV transmission system. The study seeks to determine the effect of the FACTS device on the transmission system. The selected case study transmission system comprises of six buses (with one generation bus) and five transmission lines. The relevant data concerning the case study buses and transmission lines are given in Table 1 and Table 2.

Table : The per unit voltages and phase angle of the existing 330KV network

Bus Number	Per Unit Voltage	Voltage	Angle in degree
1	1. 0000	330.00	-4.73
2	0.9699	320.07	-7.28
3	1.0030	330.99	-3.49
4	1.0212	336.99	-4.64
5	1.0000	330.00	0.63
6	1.0000	330.00	-3.69

Table 2: The transmission line parameters for the 330KV Network

Transmission Line Number	Circuit type	Length of line (Km)	Line Impedance : X(pu)	Line Impedance : R (pu)
1	Double	25	0.0006	0.0043
2	Double	50	0.0009	0.0070
3	Single	63	0.0025	0.0186
4	Single	32	0.0009	0.0072
5	Single	107	0.0042	0.0316

III. RESULTS AND DISCUSSION

A. VOLTAGE PROFILE RESULTS

Table 3 shows the result results of the simulation with and without IPFC on the voltage profile of the transmission lines using MATLAB.

Table 3; Voltage profile of buses with and without the IPFC devices

Bus Number	Simulated Voltage without IPFC	Simulated Voltage with IPFC
1	- .2088	1.0000
2	1.0005	0.9841
3	1.0052	1.0000
4	1.0019	1.0000
5	0.1158	1.0000
6	1.0000	1.0000

Figure 4 is the comparison of the voltage profile of the buses with IPFC and without IPFC; it is plotted from the voltage without the IPFC data of Table 3, the x-axis represents the locations of buses with their serial numbers. From Figure 4 the bus with the least voltage is located at bus number 1, but the voltage from the second bus to the fourth bus were normalized with just Newton-Raphson models without applying the IPFC device.

Also, apart from the bus number 2 with voltage of 0.9841 pu, the other buses were normalized at 1pu. This shows that the IPFC is very effective and achieved a 90% voltage improvement if inserted on the transmission line. In all, the spikes seen at the plot without IPFC were totally normalized when an IPFC device was introduced into the modeling system.

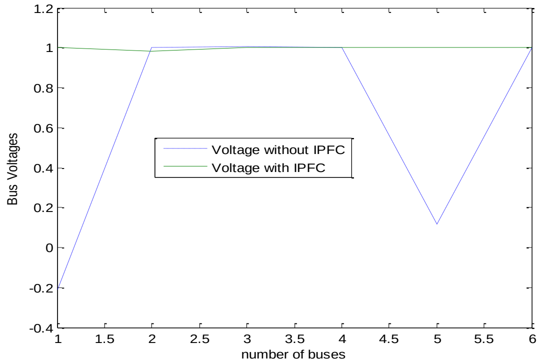

Figure 4, Voltage profile of buses with and without IPFC device

B. POWER LOSSES

The results of the comparison between the power loss with the IPFC device and without the IPFC device are shown in Table 4 and Figure 5. Without the IPFC device, the transmission line with the highest power loss in Table 4 and Figure 5 is transmission line 2 with a real power loss and reactive power loss of 66.3794 MW and 71.57289 MVar respectively. The total real power loss and reactive power loss without using the IPFC is 245.90 MW and 217.25MVar respectively. The loss incurred is very excessive which needs to be controlled to maximize profit. When the IPFC devices are used, the power losses are minimized with the highest power loss at transmission lines 3 having an active and reactive power loss of 37.0115 MW and 16.9210 Mvar respectively with a total active and reactive power loss of 186.28 MW and 38.1632MVar respectively. The power loss was minimized which shows that the IPFC device is also very effective in optimizing the power losses as well. The device was able to minimize the power loss up to 80.9% for the active power loss and 75.5% for the reactive power loss.

Table 4: Transmission lines with and without IPFC

Transmission line number	Simulated Power Loss without IPFC (MW)	Simulated Power Loss with IPFC (x 100) (MW)
1	38.1112-33.5055i	6.4085 + 9.4442i
2	66.3794-71.5728i	6.4940 + 3.8910i
3	66.2287-39.5037i	9.6150 +16.1290i
4	40.7958-33.3982i	6.4940 + 3.8910i
5	34.3805-39.2703i	8.0000 + 4.8080i
Total:	245.90-217.25i	9.6150 +16.1290i

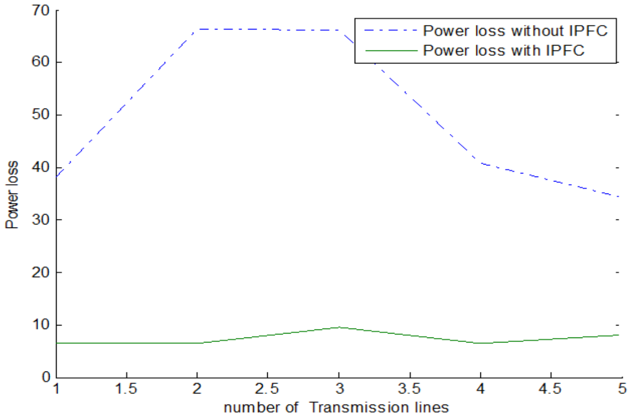

Figure 5: Plot of Power loss with and Without IPFC device.

IV. CONCLUSIONS

The interline power flow controller (IPFC) was used to optimize the power losses in the transmission lines of the South-southern part of Nigeria. It was also used to improve the voltage profile of the transmission system comprising of six buses and five transmission lines. The results of the system power flow without the IPFC and with the IPFC were compared. The total power loss obtained after inserting the IPFC was lower than the system without the IPFC. This meant that the IPFC was very effective in minimizing (optimizing) the power losses. Also the voltage profile of the system was also improved up to the required voltage of 330KV.

REFERENCES

1. Lazarou, S., Vita, V., Christodoulou, C., &Ekonomou, L. (2018). Calculating operational patterns for electric vehicle charging on a real distribution network based on renewables' production. *Energies*, *11*(9), 2400.
2. Todescato, M., Simpson-Porco, J. W., Dörfler, F., Carli, R., &Bullo, F. (2015, December). Optimal voltage support and stress minimization in power networks. In *2015 54th IEEE Conference on Decision and Control (CDC)* (pp. 6921-6926). IEEE.
3. Singhal, A., &Ajjarapu, V. (2017, September). Long-term voltage stability assessment of an integrated transmission distribution system. In *2017 North American Power Symposium (NAPS)* (pp. 1-6). IEEE.
4. Lee, Y., & Song, H. (2019). A Reactive Power Compensation Strategy for Voltage Stability Challenges in the Korean Power System with Dynamic Loads. *Sustainability*, *11*(2), 326.
5. Chayapathi, V., Sharath, B., &Anitha, G. S. (2013). Voltage collapse mitigation by reactive power compensation at the load side. *Int. J. Res. Eng. Tech*, *2*(9), 251-257.
6. Nguyen, H. D., &Turitsyn, K. (2015). Voltage multistability and pulse emergency control for distribution system with power flow reversal. *IEEE Transactions on Smart Grid*, *6*(6), 2985-2996.
7. Barán, B., Vallejos, J., Ramos, R., &Fernández, U. (2001). Multi-objective reactive power compensation. In *2001 IEEE/PES Transmission and Distribution Conference and Exposition. Developing New Perspectives (Cat. No. 01CH37294)* (Vol. 1, pp. 97-101). IEEE.
8. Thuan T. N. and Anh V.T.,(2015); Distribution network reconfiguration for power loss minimization and voltage profile improvement using cuckoo search algorithm, *Electrical Power and Energy Systems*, 68: 233-242.
9. Mohanty, A. K., &Barik, A. K. (2011). Power system stability improvement using FACTS devices. *International Journal of Modern Engineering Research (IJMER)*, *1*(2), 666-672.
10. Singh, B., &Agrawal, G. (2018). Enhancement of voltage profile by incorporation of SVC in power system networks by using optimal load flow method in MATLAB/Simulink environments. *Energy Reports*, *4*, 418-434.
11. Kumar, S., & Kumar, N. (2011). Effectiveness of FACTS devices for power system stability enhancement. *International Journal of Advances in Engineering Sciences*, *1*(2), 1-4.
12. Farooq, A. (2018). Influence of Unified Power Flow Controller on Flexible Alternating Current Transmission System Devices in 500 kV Transmission Line. *Journal of Electrical and Electronic Engineering*, *6*(1), 12.
13. Ahmad, S., Albatsh, F. M., Mekhilef, S., &Mokhlis, H. (2014, May). An approach to improve active power flow capability by using dynamic unified power flow controller. In *2014 IEEE Innovative Smart Grid Technologies-Asia (ISGT ASIA)* (pp. 249-254). IEEE.
14. Hingorani, N. G. and L. Gyugyi, (1999); Understanding *FACTS: concepts and technology of flexible AC transmission systems*, France, Wiley-IEEE Press, p:51-295.
15. Pandey, A. K. R., &Kori, A. K. (2012). Real and reactive power flow control using flexible ac transmission system connected to a transmission line: A Power Injection Concept. *International Journal of Advanced Research in Computer Engineering & Technology (IJARCET)*, *1*(6), 252-256.
16. Dixon, J., Moran, L., Rodriguez, J., &Domke, R. (2005). Reactive power compensation technologies: State-of-the-art review. *Proceedings of the IEEE*, *93*(12), 2144-2164.
17. Kumar, C. K., Kumar, M. S., SriramBabu, V., &Nagulmeera, S. (2013). A comparative analysis of UPFC as a Power Flow controller with applications. *IOSR Journal of Electrical and Electronics Engineering*, *4*(6).
18. Singh, R. P., Bharadwaj, S. K., & Singh, R. K. (2014). Flexible AC transmission system controllers: A state of art. *International Journal*

of Electronic and Electrical Engineering, *7*(8), 843-850.

19. Tyll, H. K., &Schettle, F. (2009, March). Historical overview on dynamic reactive power compensation solutions from the begin of AC power transmission towards present applications. In *2009 IEEE/PES Power Systems Conference and Exposition*(pp. 1-7). IEEE.
20. Gelen, A., & YALÇINÖZ, T. (2010). Experimental studies of a scaled-down TSR-based SVC and TCR-based SVC prototype for voltage regulation and compensation. *Turkish Journal of Electrical Engineering & Computer Sciences*, *18*(2), 147-158.
21. Kojima, T., Isotani, H., & Yamada, M. (2017). Distribution Static Var Compensators and Static Synchronous Compensators for Suppressing Voltage Fluctuation. *FUJI ELECTRIC REVIEW*, *63*(1), 36-40.
22. Lima, M. C., &Tyll, H. (2002, October). An overview of static VAR compensators technology evolution on a Brazilian generation and transmission utility. In *10th International Conference on Harmonics and Quality of Power. Proceedings (Cat. No. 02EX630)* (Vol. 2, pp. 601-606). IEEE.
23. Singh, B., Saha, R., Chandra, A., & Al-Haddad, K. (2009). Static synchronous compensators (STATCOM): a review. *IET Power Electronics*, *2*(4), 297-324.
24. Wei, W. H., Liu, W. H., Song, Q., Yuan, Z. C., Ni, L., &Zou, B. (2005, February). Research on fast dynamic control of static synchronous compensator using cascade multilevel inverters. In *ZhongguoDianjiGongchengXuebao(Proc. Chin. Soc. Electr. Eng.)* (Vol. 25, No. 3, pp. 23-28).
25. Yarlagadda, V., Ram, B. S., &Rao, K. R. M. (2012). Automatic control of thyristor controlled series capacitor (tcsc). *International Journal of Engineering Research and Applications (IJERA)*, *2*(3), 444-449.
26. Bandekar, P. J., Mulla, A. M., &Atre, Y. R. (2015). Tyristor Controlled Series Capacitor with Automatic Control. *International Journal of Innovations in engineering research and technology*, *2*(4).
27. Kumar, P. S. P., Vijaysimha, N., &Saravanan, C. B. (2013). Static synchronous series compensator for series compensation of EHV transmission line. *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, *2*(7).
28. Ustun, T. S., &Mekhilef, S. (2010). Effects of a static synchronous series compensator (SSSC) based on a soft switching 48-pulse PWM inverter on the power demand from the grid. *Journal of Power Electronics*, *10*(1), 85-90.
29. Gyugyi, L., Sen, K. K., &Schauder, C. D. (1999). The interline power flow controller concept: a new approach to power flow management in transmission systems. *IEEE transactions on power delivery*, *14*(3), 1115-1123.
30. KRISHNAN, G. R., &Gopalakrishnan, V. (2013). APPLICATION OF AN INTERLINE POWER FLOW CONTROLLER AS AGC. *Journal of Theoretical & Applied Information Technology*, *54*(3).
31. Singh, R. P., Bharadwaj, S. K., & Singh, R. K. (2014). Flexible AC transmission system controllers: A state of art. *International Journal of Electronic and Electrical Engineering*, *7*(8), 843-850.
32. Mohanty, A. K., &Barik, A. K. (2011). Power system stability improvement using FACTS devices. *International Journal of Modern Engineering Research (IJMER)*, *1*(2), 666-672.
33. Karthik, B., &Chandrasekar, S. (2012). Modeling of IPFC for power flow control in 3-phase line-further aspects and its limitations. *International Journal of Computer and Electrical Engineering*, *4*(2), 227.
34. Babu, A. N., Sivanagaraju, S., Padmanabharaju, C., &Ramana, T. (2010). Multi-line power flow control using interline power flow controller (IPFC) in power transmission systems. *World Academy of Science, Engineering and Technology, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering*, *4*(3), 577-581.
35. Saxena D. R. (2013) Multi-Line power Flow Control Using Interline Power Flow Controller (IPFC) in Power Transmission system. International Journal Of Engineering And Computer Science ISSN:2319-7242 Volume 2 Issue 11 November, 2013 Page No. 3089-3093