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Effect of Current Based Unified Power Flow Controller under Single Line Outage Condition

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Abstract: *The Unified Power Flow Controller (UPFC) has the capability to control the shunt voltages and the line power flows. This type of device has to be installed in a proper location to get the maximum benefit from it. In this paper, Current Based Model (CBM) has been developed. Under Single Transmission Line outage (STLO), Line Outage Distribution Factor (LODF) was computed for identification of the location for installing UPFC. Standard 5 – bus system is considered for simulation purpose in MATLAB environment.*

Keywords: *unified power flow controller, current based model, single transmission line outage, line outage distribution factor*

I. Introduction

Power Generation and Transmission is a complex process, wherever power is to be transferred, the two main components are active and reactive power. In a three phase ac power system active and reactive power flows from the generating station to the load through different transmission lines and networks buses. The active and reactive power flow in transmission line is called power flow or load flow. Power flow studies provide a systematic mathematical approach for determination of various bus voltages, there phase angle, active and reactive power flows through different lines, generators and loads at steady state condition.The continuing rapid development of high-power semiconductor technology now makes it possible to control electrical power systems by means of power electronic devices [1]. These devices constitute an emerging technology called FACTS (flexible alternating current transmission systems) [2]. Unified power flow controller (UPFC) [3,4] can be used for power flow control, loop-flow control, load sharing among parallel corridors, enhancement of transient stability, mitigation of system oscillations and voltage (reactive power) regulation. The implementation of such equipment's requires the different power electronics-based compensators and controllers [5]. The FACTS devices use various power electronics devices such as Thyristors, Gate turn offs(GTO), Insulated gate bipolar transistors(IGBT), Insulated Gate Commutated thyristors (IGCT), they can be controlled very fast as well as different control algorithms adapted to various situations.

In this environment, high performance control of the power network is mandatory [6–8]. Flexible ac transmission system (FACTS) devices give more flexibility of control for secure and economic operation of power systems [9]. Among FACTS devices, the unified power flow controller (UPFC) is emerging as a promising solution for improving power system characteristics for its high degree of controllability of many power system variables [10]. By use of controllable components, such as controllable series capacitors and phase shifters, the line flows can be changed in such a way that thermal limits are not exceeded, losses minimized, stability margins increased, contractual requirements fulfilled etc., without violating economic dispatch [11]. Quasi-Newton methods accelerate the steepest-descent technique for function minimization by using computational history to generate a sequence of approximations to the inverse of the Hessian matrix [12]. The most accurate approach for modelling the steady state behaviour of balanced, three phase, electric power systems is through the solution of the power flow [13].

UPFC cannot only perform the functions of the static synchronous compensator (STATCOM), thyristor switched capacitor (TSC) thyristor controlled reactor (TCR), and the phase angle regulator but also provides additional flexibility by combining some of the functions of the above controllers. Both the magnitude as well as the phase angle of the voltage can be varied independently. Power System fast line flow calculation for security control by sensitivity factor.

II. Line Outage Distribution Factor

Line Outage distribution factors are applied to the testing of overloads when transmission circuits are lost. By definition, i.e., from equation (1) the line outage distribution factor has the following meaning:

$$d_{l,k} = \frac{\Delta f_l}{f_k^0} \quad (1)$$

Where

$d_{l,k}$ = line outage distribution factor when monitoring line *l* after an outage on line *k*

Δf_l = Change in MW flow on line *l*

f_k^0 = Original flow on line *k* before it was outaged (opened)

If one knows the power on line *l* and line *k*, the flow on line l with line k out can be determined using "d" factors as shown in equation (2):

$$f_l = f_l^0 + d_{l,k} f_k^0 \quad (2)$$

where

f_l^0, f_k^0 = Preoutage flows on lines *l* and *k*, respectively

f_l = flow on line *l* with line *k* out

By precalculating the line outage distribution factors, a very fast procedure can be set up to test all lines in the network for overload for the outage of a particular line. Furthermore, this procedure can be repeated for the outage of each line in turn, with overloads reported to the operations personnel in the form of alarm messages [14].

1. Current Based Model

The developed model represents the UPFC in steady state, introducing the current in the series converter as variable as shown in Fig. 1.

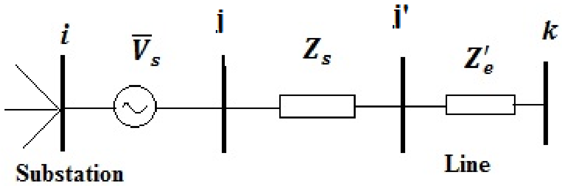

Fig. 1 UPFC and network

Series voltage: V_s

Series transformer impedance: Z_s

Transmission line impedance: $Z_e^{'}$

Let us consider busbar *i* and *k* existent in the transmission line where the UPFC will be located, with impedance $Z_e^{'}$. Fictitious busbars *j* and *j'* and are created in order to include the UPFC in the system. The series impedance of UPFC coupling transformer Z_s and the transmission line are added, resulting in the equivalent impedance $Z_e = Z_e^{'} + Z_s$ connected to the internal node *j* and *j'* node is eliminated. This association is quite simple, even in case of two port lines represented by π circuits. The equivalent network is presented in Fig. 2, with the series voltage inserted between busbars *i* and *j*.

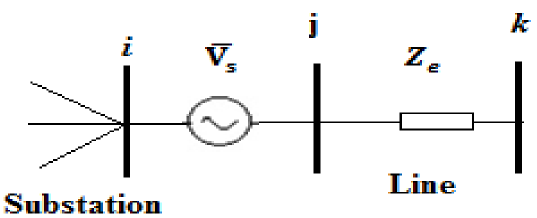

Fig. 2 Equivalent model of UPFC in the electric network

3.1 Injected Power Due to Current

The power consumption of the system load at busbar *i* is called S_i^0.

Additional powers S_i^c and S_j^c, due to current $\overline{I}$, are easily calculated according to Fig. 3 and also through the equations (3) and (6). Current $\overline{I}$ introduces two variables I, φ related to module and phase of the current.

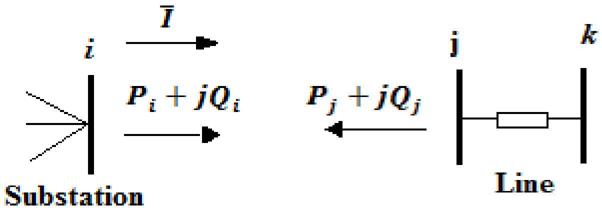

Fig. 3 Injected power due to current in busbars *i* and *j*

New power terms due to current:

$$S_i^c = \overline{V}_i \overline{I}^* \quad (3)$$

$$P_i^c = V_i I \cos(\varphi - \delta_i) \quad (4)$$

$$Q_i^c = V_i I \sin(\varphi - \delta_i) \quad (5)$$

The new real and reactive power due to current at bus *i* are shown in the equations (4) and (5):

$$S_j^c = -\overline{V}_j \overline{I}^* \quad (6)$$

$$P_j^c = -V_j I \cos(\varphi - \delta_j) \quad (7)$$

$$Q_j^c = -V_j I \sin(\varphi - \delta_j) \quad (8)$$

The new real and reactive powers due to current at bus j are shown in the equations (7) and (8):

$$P_i = P_i^0 + P_i^c \quad (9) \qquad P_j = P_j^c \quad (10)$$

$$Q_i = Q_i^0 + Q_i^c \quad (11) \qquad Q_j = Q_j^c \quad (12)$$

Equations (9) and (10) represent the total real power due to injected current and equations (11) and (12) represent the total reactive power due to injected current.

3.2 Series Voltage Equations

The following treatment of the series voltages for the UPFC is general for FACTS devices that can employ this feature. The main example is the SSSC and, as a consequence, other equipment such as IPFC and GIPFC that use series voltage can be modeled as well.

Equation (13) represents voltage equation between nodes *i* and *j*:

$$\overline{V}_j - \overline{V}_i = \overline{V}_s \quad (13)$$

The series voltage will be treated similarly to the PIM model as shown in equation (14):

$$\overline{V}_s = rV_i e^{j\gamma} \quad (14)$$

Where *r* is the factor for series voltage and □is the series voltage angle.

Equation (14) is substituted in equation (13) results in the following equation:

$$\overline{V}_j - (1 + re^{j\gamma})\overline{V}_i = 0 \quad (15)$$

If *r* and □are constants, in a regular power flow case, calling the complex variable:

$$A\angle\alpha = -(1 + r\angle\gamma) \quad (16)$$

Substituting equation (16) in equation (15), then equation (17) is obtained:

$$\overline{V}_j + A\angle\alpha.\overline{V}_i = 0 \quad (17)$$

Obtain the equations (18) and (19), relative to the real and imaginary parts, $F_n = 0$ and $G_n = 0$, respectively:

$$F_n = AV_i \cos(\alpha + \delta_i) + V_j \cos\delta_j \quad (18)$$

$$G_n = AV_i \sin(\alpha + \delta_i) + V_j \sin\delta_j \quad (19)$$

3.3 Power Balance

In order to complete the UPFC model, it is necessary to introduce the power balance equation between series and shunt converters. The series power will be added to the shunt power of busbar *i* as shown in Fig. 4.

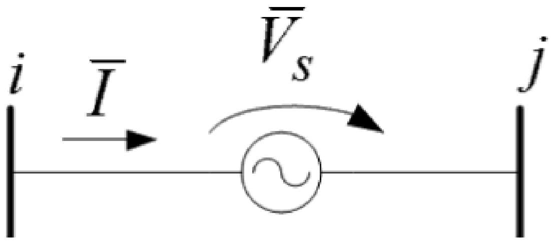

Fig. 4 UPFC series voltage power

Calculate the power in the series converter as shown in equation (20):

$$S_s = re^{j\gamma}\overline{V}_i I\angle -\varphi \qquad (20)$$

Splitting the previous expression in active and reactive powers and equating to the real and imaginary part, equations (21) and (22) are obtained:

$$P_s = rV_i I\cos(\delta_i + \gamma - \varphi) \qquad (21)$$

$$Q_s = rV_i I\sin(\delta_i + \gamma - \varphi) \qquad (22)$$

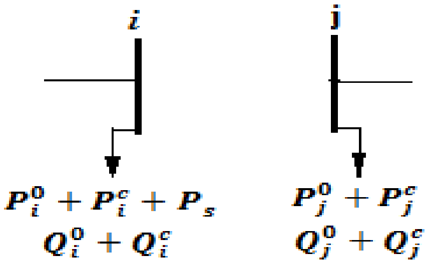

Fig. 5 Injected powers in the busbars with the inclusion of UPFC

Active power P_s is included in node *i* as shown in Fig. 5.

After incorporating UPFC the change in the real and reactive power equations are shown below:

$$P_i^{'} = P_i^0 + P_i^c + P_s = P_i^0 + V_i I\cos(\varphi - \delta_i) + rV_i I\cos(\delta_i + \gamma - \varphi) \qquad (23)$$

$$P_j^{'} = P_j^0 + P_j^c = P_j^0 - V_j I\cos(\varphi - \delta_j) \qquad (24)$$

$$Q_i^{'} = Q_i^0 + Q_i^c = Q_i^0 + V_i I\sin(\varphi - \delta_i) \qquad (25)$$

$$Q_j^{'} = Q_j^0 + Q_j^c = Q_j^0 - V_j I\sin(\varphi - \delta_j) \qquad (26)$$

The equations P_i^c, P_j^c, Q_i^c, Q_j^c are the real and reactive powers due to injected current. The equations $P_i^{'}$, $P_j^{'}$, $Q_i^{'}$, $Q_j^{'}$ are the real and reactive power equations after incorporating UPFC at bus *i* and *j* as represented in equations (23), (24), (25) and (26). The equations P_i^0, Q_i^0, P_j^0, Q_j^0 are real and reactive power equations without UPFC.

III. Proposed Algorithm

1. Read the system data.
2. Run the load flow without the line outage contingency and use the results as base case.
3. Create line outage contingency for different lines and obtain load flow results.
4. Rank the more sensitive line under line outage condition which has highest value of line outage distribution factor.
5. Install UPFC based on current based model in highly sensitive line where line outage distribution factor is high.
6. Compare the variation in voltage and real power (P) loss with and without UPFC.

IV. Case Study and Results

To show the robustness of the proposed algorithm, standard-5 bus system has been considered which consists of 1 – slack bus, 1 – generator bus and 3 – load buses. Line outage distribution factors are shown in TABLE I. Considering both the load buses for a transmission line connected between bus 4 and bus 5 which has highest value of line outage distribution factor i.e., 1.048072. UPFC installation is near bus 4 on the line 4 – 5.

Table:1 Line Outage Distribution Factor

Line	Line Outages						
	1 to 2	**1 to 3**	**2 to 3**	**2 to 4**	**2 to 5**	**3 to 4**	**4 to 5**
1 to 2	1	1.044697	0.325792	0.303488	0.17417	0.496624	0.261261
1 to 3	1.130286	1	0.359477	0.334339	0.290404	0.480663	0.254054
2 to 3	0.384686	0.3717	1	0.381288	0.304933	0.560467	0.291892
2 to 4	0.397371	0.420797	0.452489	1	0.525022	0.690608	0.499099
2 to 5	0.194514	0.216072	0.229764	0.322602	1	0.537139	1.046847
3 to 4	0.593714	0.606299	0.655103	0.678739	0.557309	1	0.518919
4 to 5	0.193143	0.205651	0.220211	0.307176	1.048072	0.33763	1

4.1 Variation of ‘r’ value

Fig. 6 represents voltage magnitude at bus-4 for different values of ‘r’ ranging from 0 to 0.1. For a constant value of ‘γ’=210° if ‘r’ is increased the magnitude of the voltage is increased upto a certain value.

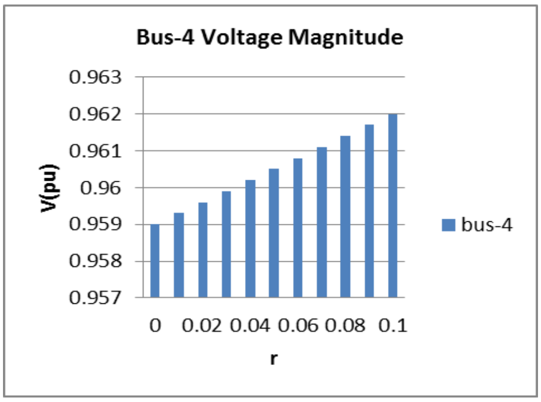

Fig. 6 Voltage magnitude at bus-4 by varying ‘r’ value

Fig. 7 represents voltage magnitude at bus-5 for different values of ‘r’ ranging from 0 to 0.1. For a constant value of ‘γ’=210° if ‘r’ is increased the magnitude of the voltage is increased upto a certain value.

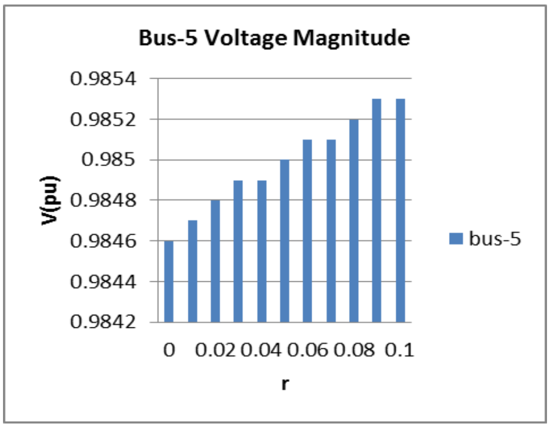

Fig. 7 Voltage magnitude at bus-5 by varying ‘r’ value

4.2 Variation of ‘γ’ value

Fig. 8 represents voltage magnitude at bus-4 for different values of ‘γ’ ranging from 0 to 360 degrees. As the value of γ increases, the magnitude of the voltage increases upto 180 degrees and then decreases.

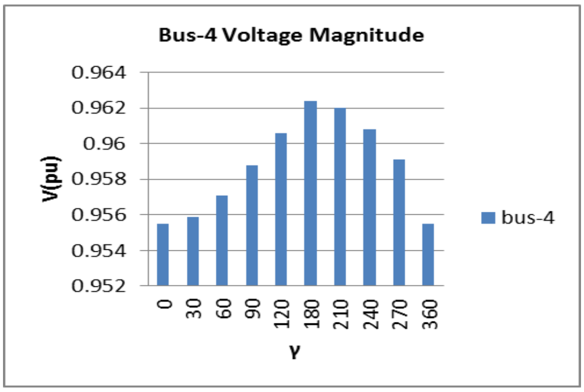

Fig. 8 Voltage magnitude at bus-4 by varying ‘γ’ value

Fig. 9 represents voltage magnitude at bus – 5 for different values of ‘γ’ ranging from 0 to 360 degrees. As the value of γ increases, the magnitude of the voltage increases upto 180 degrees and then decreases.

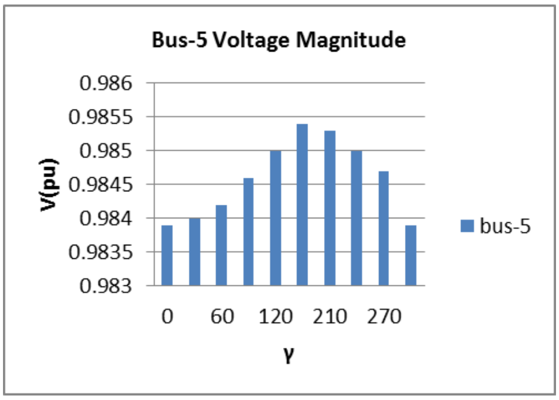

Fig. 9 Voltage magnitude at bus-5 by varying ‘γ’ value

The magnitude of voltage at each bus with and without UPFC is represented in TABLE II. The total real and reactive power loss with and without UPFC is included in TABLE III. From below tables, it is observed that the magnitude of voltage at each load without UPFC is slightly more than the magnitude of voltage at same load bus with UPFC. Therefore, the current flowing between load buses is reduced due to slight variation in voltage magnitude after incorporating UPFC. As the current decreases, the real power loss is also decreased in the lines between load buses. Therefore, the total real power loss and reactive power loss of standard 5 – bus system has been reduced as shown in TABLE III.

Table:2 Magnitude Of Voltage With And Without UPFC

Bus	Without UPFC	With UPFC
1.	1.05	1.05
2.	1.00	1.00
3.	0.9841	0.986
4.	0.9816	0.985
5.	0.9708	0.9853

Table:3 Active and Reactive Power Loss with and without UPFC

	Without UPFC	With UPFC
Active power loss (MW)	56.7	38.24
Reactive power loss (MVAR)	11.65	9.44

V. Conclusion

Thus the performance of UPFC in an IEEE – 5 bus system was presented based on current based model. The location of UPFC has been identified by using line outage distribution factor i.e., between bus 4 and bus 5. Voltage magnitudes at load buses are observed by varying the ‘r’ value and ‘γ’ value. The magnitude of voltage at load buses has been increased after incorporating UPFC in the system. The total real and reactive power losses are reduced by using UPFC.

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