Determination of Optimal Location of FACTS Devices for Power System Restoration Including Load Flow and Contingency Analysis

Goutham N S
Student, Dept. of EEE
Ghousia College of Engineering
Ramanagaram, Karnataka, India
Affiliated to VTU, Belagavi

Dr. Mohd. Z. A. Ansari, Member IEEE
Professor and Head, Dept. of EEE
Ghousia College of Engineering
Ramanagaram, Karnataka, India
Affiliated to VTU, Belagavi

***Abstract* – This paper deals with improvement of the power system for better and efficient use of power and improving the reliability of the system under contingencies. The system is subjected to contingencies such as line outages and generator outages. The voltage profile, active and reactive power flows for IEEE 6 bus test system is checked for pre-contingencies and post-contingencies using NR method of load flow analysis. The voltage sags and swells & reactive power flows at each bus and transmission lines for test system are studied & suitable reactive power compensation is incorporated using FACTS devices by identifying the optimal location thereby restoring the power system to normal condition.**

***Index Terms*– Load flow analysis (LFA), contingency analysis, optimal location, FACTS controllers, system restoration.**

I. INTRODUCTION

Due to the increase in population growth and urbanization there is an increase in power demand in day to day life. It is necessary to meet the rising power demand for power utilities, industries and commercial purpose. So there is a need for planning and forecasting the present and future load demand and to use the available power smartly and efficiently. Smartness includes upgrading the existing generation, transmission and distribution network efficiently and developing the new technology without much initial cost of investment and which can be adopted in the present power system [1]. The communication technologies play a vital role in upgrading the power system network. Efficiency depends on how much the power system components work efficiently in day to day life without power interruption. A power system is said to be efficient if the power system equipment's can operated to their prescribed life time [2]. Due to various conditions such as abnormal weather conditions and continuous momentary faults in the power system the life of the power system components gets reduced. It is necessary to prevent the unnecessary momentary faults by incorporating well equipped and fast acting CB's and relays [3]. The reactive power consumption is increasing day by day since most of the loads are inductive in nature. Though the generating station do not supply reactive power to the consumer end there is a shortage of reactive power due to the use of more inductive loads and transmission & distribution losses [4]. Therefore there is a need of incorporating FACTS controllers at the transmission end and DG's at the generator side.

II. PROBLEM FORMULATION

This paper deals with the improvement of power system for the better and efficient use of quality power and improving the reliability of the system under contingencies. The voltage profile at each bus, active and reactive power flows of each transmission line is checked for pre-contingencies and post-contingencies for IEEE 6 - bus test system using NR method of load flow analysis. The threshold voltage levels are 0.95 per unit to 1.05 per unit. TCSC is incorporated between the lines which causes voltage drop at the bus and also allows more reactive power to flow during contingency condition. The main aim of placing FACTS controllers is to improve the voltage profile, line flows and thereby to reduce overall losses in the test system.

A. Description of the System

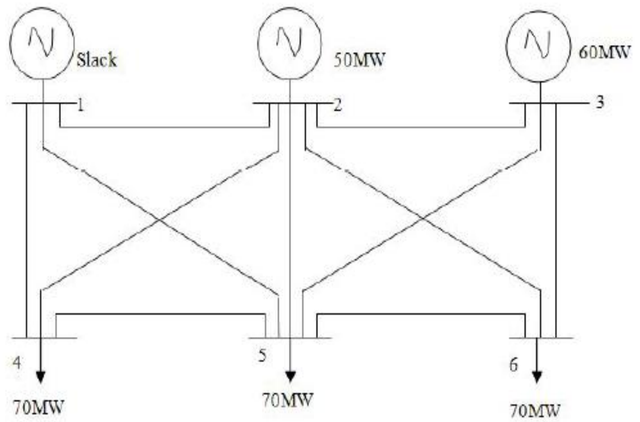

Fig. 1: IEEE- 6 Bus Test Systems

IEEE- 6 bus system is shown in Fig.1 has 3 generators, 3 loads and 11 transmission line connected to 6 bus and the bus voltages is maintained between 0.95 p.u to 1.05 p.u. The test system has 1 slack bus and 2 PV bus. The slack bus voltage is specified and for the PV bus the voltage magnitude real and reactive power limits are specified. The system is tested for a De-rated MVA of 100MVA, 220kV transmission line.

B. *System data*

TABLE 1: TRANSMISSION LINE DATA

From Bus	To Bus	R(p.u)	X(p.u)	B/2(p.u)	Capacity (MW)
1	2	0.1	0.2	0.0.2	30
1	4	0.05	0.3	0.02	50
1	5	0.08	0.25	0.03	40
2	3	0.05	0.25	0.03	20
2	4	0.05	0.1	0.01	40
2	5	0.1	0.3	0.02	20
2	6	0.07	0.2	0.025	30
3	5	0.12	0.26	0.025	20
3	6	0.02	0.1	0.01	60
4	5	0.2	0.4	0.04	20
5	6	0.1	0.3	0.03	20

TABLE 2: BUS DATA

Bus number	Bus type	V (p.u)	P_g (MW)	Q_g (MVAR)
1	Slack	0.1	-	-
2	PV	0.05	50	0.02
3	PV	0.08	60	0.03
4	PQ	0.05	0	0
5	PQ	0.05	0	0
6	PQ	0.1	0	0

TABLE 3: LOAD DATA

Bus number	LOAD	
	P (MW)	Q (MVAR)
4	PV	0.05
5	PV	0.08
6	70	70

III. METHODOLOGY PROPOSED

A. *Newton Raphson Method*

Load flow studies are a major aspect in solving any load flow problem. From load flow studies voltage magnitude, phase angles, active and reactive power flows through a transmission line can be obtained for pre-contingency case and post-contingency case. The exact situation of the power system can be obtained using load flow studies. N-R method of load flow studies gives more accurate results compared to other load flow studies and has fast computational time.

The relation between voltage and current at any 'n" bus system is given by

$$I_i = \sum Y_{ij} V_{ij} \quad \text{For i=1, 2 ....n} \tag{1}$$

The expression for active and reactive power injection is given by

$$P_i = Re\left[V_i \sum_{j=1}^{n} Y_{ij}^* V_j^*\right] \text{ For i=1, 2 ....n} \tag{2}$$

$$Q_i = Im\left[V_i \sum_{j=1}^{n} Y_{ij}^* V_j^*\right] \text{ For i=1, 2 ....n} \tag{3}$$

$$V_i = |V_i| \angle \theta_i \ ; \ \theta_{ij} = \theta_i - \theta_j \tag{4}$$

$$P_i = |V_i| + \sum_{j=1}^{n} ((G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \, |V_j|) \tag{5}$$

$$Q_i = |V_i| + \sum_{j=1}^{n} ((G_{ij} \sin \theta_{ij} + B_{ij} \cos \theta_{ij} \, |V_j|) \tag{6}$$

The aim of load flow studies is to find the power mismatch both active and reactive power mismatch.

$$\Delta P_i = P_i^{sp} - P_{i,cal} \tag{7}$$

$$\Delta Q_i = Q_i^{sp} - Q_{i,cal} \tag{8}$$

B. *Voltage Performance Index (PI_v)*

The inability of the power system to operate within the prescribed limits due to violation of bus voltages is described by the voltage performance index.

$$PI_v = \sum_{i=1}^{n} \left(\frac{W}{2z}\right) \left\{\frac{|V_i| - |V_i^{sp}|}{\Delta V_i^{lim}}\right\}^{2z} \tag{9}$$

$|V_i|$ is the bus voltage magnitude.

$|V_i^{sp}|$ is the i^th bus specified voltage magnitude.

ΔV_i^{lim} is the voltage deviation limit.

z is the exponent of the penalty function and value is (=1)

n is the number of buses in the given power system.

W is the real non negative weighting factor and value is (=1)

Here, to calculate ΔV_i^{lim} Maximum voltage limit is 1.05 per unit and minimum voltage limit is 0.95 per unit since ±5% deviation in voltage is allowed.

IV. SIMULATION RESULTS AND DISCUSSION

A. *Test System*

The proposed methodology is tested on IEEE 6 – bus test system for pre-contingency and post-contingency condition and the voltage sags and swells at different bus and active and reactive power flows are obtained respectively.

Based on the proposed methodology, the test system is run for NR load flow studies and results are simulated.

B. Assumptions and Constraints

The following are the assumptions made and constraints observed:

i. The lower and upper limit of voltages in per unit is 0.95and 1.05 respectively.

ii. The TCSC is placed in such a way where the line is most sensitive which affect both voltage magnitude of individual bus and reactive power flow in the lines.

TABLE 4: RANKING OF THE LINES

Tripped Line	PI_v	Rank
1-2	0.7686	11
1-4	3.570	1
1-5	1.2732	4
2-3	0.7726	9
2-4	1.4846	3
2-5	0.8368	8
2-6	1.0033	5
3-5	0.86638	7
3-6	1.8576	2
4-5	0.8852	6
5-6	0.7707	10

TABLE 5: PRE-CONTINGENCY AND POST-CONTINGENCY VOLTAGES FOR LINE OUTAGE (3-5) AND (3-6)

Bus No.	Pre-contingency voltage (p.u) for 3-5 and 3-6 line outage		Post-contingency voltage (p.u) for 3-5 and 3-6 line outage	
	3-5	3-6	3-5	3-6
1	1.05	1.05	1.05	1.05
2	1.05	1.05	1.05	1.05
3	1.07	1.07	1.07	1.07
4	0.9520	0.9520	0.9492	0.9492
5	0.9902	0.9902	0.9816	0.9820
6	1.0055	1.0055	1.0043	0.9016

From Table-4 it is seen that the outage of line 1-4 has more PI_v value but the line is connected to the generator bus in practice the line which is far away from the generator is affected by fault most of the times i.e. the line 3-6 and 3-5. In order to choose between these lines load flow analysis is carried out and also overloading parameter is considered.

From Table-5 it can be seen that for line outage 3-5 at bus 4 the voltage drops down to 0.9492 and for line outage 3-6 the voltage at bus4 drops to 0.9492 and also at bus 6 the voltage drops down to 0.9016 which is below 0.95 per unit lower level threshold voltage. So for the placement of TCSC the line which is more sensitive for contingency is taken to consideration further to choose between line 3-5, 3-6 % loading of the line under 3-5 and 3-6 line outage is considered.

TABLE 6: PERCANTAGE OF LINE LOADING AFTER 3-5 AND 3-6 LINE OUTAGE

Line No.	For 3-5 line outage	For 3-6 line outage
	% of loading	% of loading
1-2	10.3	5.6
1-4	50.5	51.0
1-5	89.6	90
2-3	12.7	28.0
2-4	35.3	34.1
2-5	78.6	80.4
2-6	25.3	72.4
3-5	open	33.7
3-6	73.3	Open
4-5	15.3	16.5
5-6	12.8	34.6

From Table-6 it is clear that by the removal of line 3-5 effects the lines 1-2, 2-3, 4-5 5-6 and the lines are under loaded between 0 - 25%. From these results we can depict that 3-5 is the most sensitive line. TCSC is placed between the bus 3 and bus 5 to improve the voltage magnitude at bus 2 and bus 4. The rating of the TCSC is determined by the difference of base case reactive power flow to contingency case reactive power flow through the line 3-5.

TABLE 7: BUS VOLTAGES AFETR PLACEMENT OF TCSC PLACED BETWEEN BUS 3 AND BUS 5

Bus No.	Post contingency voltage after placement of TCSC (p.u)
1	1.05
2	1.05
3	1.07
4	0.9502
5	0.9847
6	1.0049

After the placement of TCSC between bus 3 and bus 5 improvement of voltage at bus 4 and bus 5 is observed as given in Table-7. Further, reactive power loss before placing TCSC during 3-5 line outage was 36.67796 Mvar and after the placement of TCSC the losses was found to be 31.818Mvar. Hence, reduction in losses observed was about 13.25%.

V. CONCLUSIONS

In this paper, voltage performance index method is utilized for contingency analysis and for ranking of lines. Based on PI_v values the test system is analyzed for voltage sags. During contingency period voltage at bus 4 and bus 6 were effected. TCSC is placed based on voltage sags at different buses and, percentage loading of lines based on active and reactive power flow. After the placement of TCSC between the buses 3 and 5 the system is analyzed for voltage improvement and was observed that there is a significant increase in voltage profile at all the bus. Also, the reactive power loss is minimized and the system is restored to normal condition.

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