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APPLICATION OF UNIFIED POWER FLOW CONTROLLER FOR PERFORMANCE IMPROVEMENT OF POWER SYSTEM

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ABSTRACT

The growing demand for electricity due to population growth and industrialization often leads to heavy loading of transmission lines and voltage instability. However, conventional methods of improving voltage stability are normally slow and difficult to control. This paper employs a Unified Power Flow Controller (UPFC) for performance improvement of the Nigeria's 330kV transmission system. The result shows significant improvement in the network voltage and reduction in power losses.

1. INTRODUCTION

The rising demand for electricity in Nigeria has led to severe disturbances, breakdowns and voltage collapses. Voltage stability is the capability of a power system to maintain steady voltages at all buses or nodes in the system, under normal operating condition and after being exposed to disturbances from a given initial operating condition (Ingole and Gohokar, 2016). The major incidents causing voltage instability are insufficient supply of reactive power or excessive absorption of the reactive power from the system, large distance between the sending and receiving end voltages, sudden increase in load demand in a heavily stressed network (Chowdhury et.al, 2015). The aforementioned causes of voltage instability when left unattended to will result in voltage collapse and subsequently, in partial or total blackout of an entire network as a result of the cascading failure it caused.

Flexible A.C transmission system is an evolving technology used to solve power system instability problems. Its first concept was introduced by (Hingoram and Gyugyi, 1999). Since then different kinds of FACTS devices have been proposed. Flexible Alternating Current Transmission Systems (FACTS) was developed and deployed as a sustainable short-term measure to control system operation by ensuring voltage stability and increasing transmission line transfer capacity(Suchak et al., 2017). Amongst the various FACTS devices, Unified Power Flow Controller (UPFC) has a unique capability to control flow of power in multiple line and even sub-network, as against the more conventional FACT devices that control only single line power flow (Padiyar, 2007). Placing FACTS controllers at appropriate location, enhances the stability of the system. Proper installation of UPFC would ensure minimal congestion in critical lines, reduce losses on the system, and also improve stability of the system (Sharma and Gupta, 2012).

2. UNIFIED POWER FLOW CONTROLLER

The unified power flow controller is a second-generation FACTS controller. It is the most promising device in the FACTS concept. It has the ability to adjust the three control parameters, i.e., the bus voltage, transmission line reactance and phase angle between two buses. UPFC is also the most versatile FACTS controller that can be used to improve steady state stability, dynamic stability and transient stability (Onuegbu et al., 2020). Among the various FACTS devices, UPFC is regarded as the most effective version since it serves to control the three parameters at the same time. It suggests that control of transmission power can be affected by changing three parameters namely impedance, voltage magnitude and voltage angle difference between the ends of the line.

Unified power flow controller is a power electronics-based controllers that can acts as a shunt compensator, phase converters and series compensators simultaneously or separately on the transmission line (Sadikovic, 2003). The UPFC operation can be changed from one state to another without having to do generation reschedule or change line topology (Slochanal, Latha, and Chithiravelu, 2005).

The basic structure of the UPFC is shown in Fig 1. It consists of two voltage source converters and a DC circuit represented by the capacitor. Converter 1 is primarily used to provide the real power demand of converter 2 at the common DC link terminal from the AC power system. Converter 1 can also generate or absorb reactive power at its AC terminal, which is independent of the active power transfer to (or from) the DC terminal. Therefore, with proper control, it can also fulfill the function of an independent advanced static VAR compensator providing reactive power compensation for the transmission line and thus executing indirect voltage regulation at the input terminal of the UPFC.

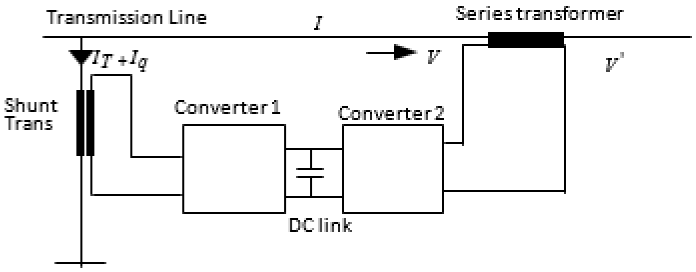

Fig 1. Schematic diagram of UPFC (Sadikovic, 2003).

Converter 2 is used to generate a voltage source at the fundamental frequency with variable amplitude ($0 \leq V_T \leq V_{Tmax}$) and phase angle ($0 \leq \Phi_T \leq 2\pi$), which is added to the AC transmission line by the series connected boosting transformer. The converter 2 output voltage injected in series with line can be used for direct voltage control, series compensation, phase shifter and their combinations. This voltage source can internally generate or absorb all the reactive power required by the different type of controls applied and transfers active power at its DC terminal.

2.1 UPFC Equivalent Circuit

Fig 2 indicates the P_{pq} representing the real power exchange between shunt and series branches. V_{pq} represents the voltage through series compensator and Q_{pq} reactive power injected by the compensator and also shown in the circuit V_S sending and V_R receiving-end voltages. Also, shown that $V_{seff} = V_S+V_{pq}$ Where, V_{seff} = Effective voltage V_S = Sending Voltage V_{pq} = Represents the voltage through series compensator

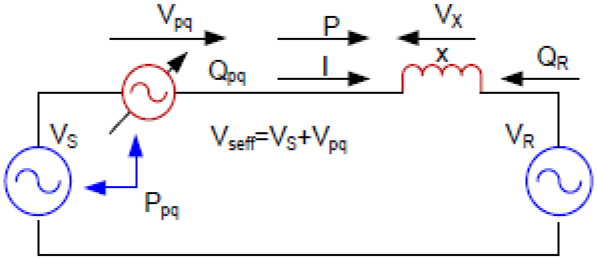

Fig. 2: UPFC operations schematic [10] (Cao and Qian, 2011).

2.2 UPFC Phasor Diagram

Fig 3(a) indicates the voltage regulation operations in UPFC. In the second Fig 3(b) indicates the line impedance compensation and management in the UPFC controller. In the third Fig 3(c) phase shifting expressed in UPFC controller and in the Fig 3-(d) indicates UPFC control parameters.

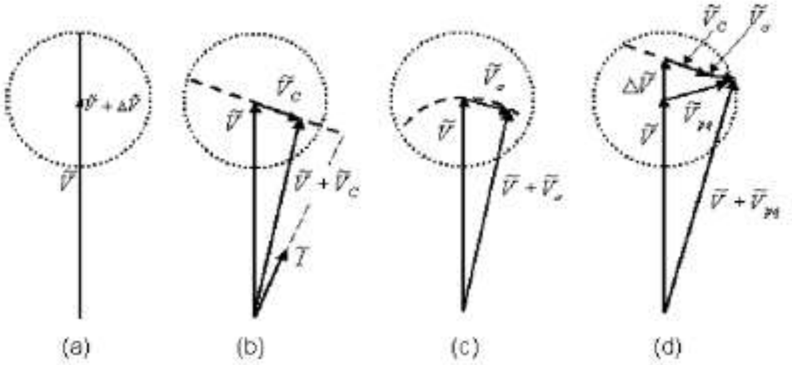

Fig 3: UPFC Phasor diagram (Abdollahi and Tavakoli, 2010).

2.3 Mathematical modelling of UPFC

A UPFC can be represented by two voltage sources representing fundamental components of output voltage waveforms of the two converters and impedances being leakage reactance of the two coupling transformers as shown in Fig 4 (Mete and Mehmet, 2007).

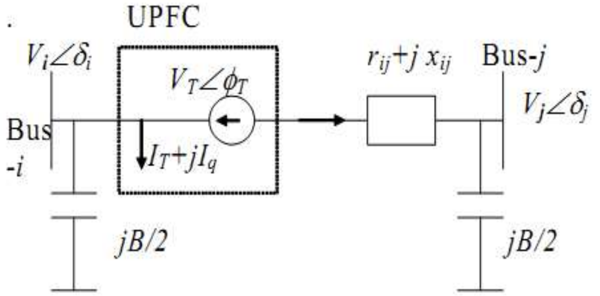

Fig 4. Equivalent circuit of UPFC (Singh and Erlich, 2005).

Based on the basic principle of UPFC and network theory, the active and reactive power flows in the line, from bus-i to bus-j, having UPFC can be written as (Verma, Singh and Gupta, 2001).

$$P_{ij} = (V_1^2 + V_T^2)g_{ij} + 2V_iV_Tg_{ij}\cos(\emptyset_T - \delta_j) - V_JV_T[g_{ij}\cos(\emptyset_T - \delta_j) + b_{ij}\left(\sin(\emptyset_T - \delta_j)\right] - V_iV_j(g_{ij}cos\delta_{ij} + b_{ij}sin\delta_{ij}) \quad (1)$$

$$Q_{ij} = -V_iI - V_i^2(b_{ij} + B/2) - V_iV_T[g_{ij}\sin(\emptyset_T - \delta_i) + b_{ij}\cos(\emptyset_T - \delta_i)] -V_iV_j(g_{ij}sin\delta_{ij} - b_{ij}cos\delta_{ij})] \quad (2)$$

Where $g_{ij} + jb_{ij} = \frac{1}{r_{ij}+jx_{ij}}$ and I_q is the reactive current flowing in the shunt transformer to improve the voltage of the shunt connected bus of UPFC. Similarly, the active and reactive power flows in the line, from bus-j to bus-i, having UPFC can be written as,

$$P_{ij} = V_j^2g_{ij} - V_jV_T[g_{ij}\cos(\emptyset_T - \delta_j) - b_{ij}\sin(\emptyset_T - \delta_j)] -V_iV_j(g_{ij}cos\delta_{ij} - b_{ij}sin\delta_{ij}) \quad (3)$$

$$Q_{ji} = -V_j^2(b_{ij} + {}^{B}/_{2}) - V_iV_j(g_{ij}\sin(\emptyset_T - \delta_j) - b_{ij}\cos(\emptyset_T - \delta_j)) +V_iV_j(g_{ij}sin\delta_{ij} + b_{ij}cos\delta_{ij}) \quad (4)$$

The real power and reactive power injections at bus-i with the system loading (λ) can be written as (Singh and Erlich, 2005).

$$P_i = P_{Gi} - P_{Di}^0(1 + \lambda) = \sum_{J\in N_b} P_{ij} \quad (5)$$

$$Q_i = Q_{Gi} - Q_{Di}^0(1 + \lambda) = \sum_{J\in N_b} Q_{ij} \quad (6)$$

Where,

P_{Di}^0 and $Q_{Di}^0$are the initial real and reactive power demands.

$P_{Gi}$and $Q_{Gi}$are the real and reactive power generations at bus-i respectively.

$N_b$is the number of system buses and λ is the sensitivity of system loading (Verma, Singh and Gupta, 2001).

2.4 UPFC Controller Benefits

UPFC has an exceptional capability to control independently the real and reactive power flow at any transmission angle. The sending and receiving end voltages are provided by independent power systems that are able to supply and absorb real power without any internal angular change. In practice, the situation will be different depending on the change in load angle.

3. METHODOLOGY

Newton Raphson iterative technique was adopted in this study because of its fast convergence and accuracy with small number of iterations. MATLAB program was used to perform the load flow computation and simulation. The load flow result identifies weak buses in the network. Those weak bus are considered as the possible locations for placement of unified UPFC, with a view of improving voltages in those buses to acceptable limits.

3.1 The System Description

The test system is the 24-bus Nigerian power system consist of 7 generators, 23 loads, and 39 lines as shown in Fig.2. There is an installed capacity of 6,500 MW of generated power. The system is characterized by high power losses and frequent voltage instability. The transmission grid system is also characterized by radial, fragile and long transmission lines. The existing system comprises over 11,000km of transmission lines (about 5,523km for 330kV lines and about 6,889km for 132kV lines). There are 32 Nos of 330/132 kV substations with total installed transformer capacity of 7,688MVA (equivalent to 6,534.8 MW). The distribution sector is comprised of 23,753km of 33KV lines 19,226km of 11kv lines, 679 of 33/11KV sub-stations. There are also 1790 distribution transformers and 680 injection substations. The 24-bus model of Nigerian network is as shown in Fig.5.

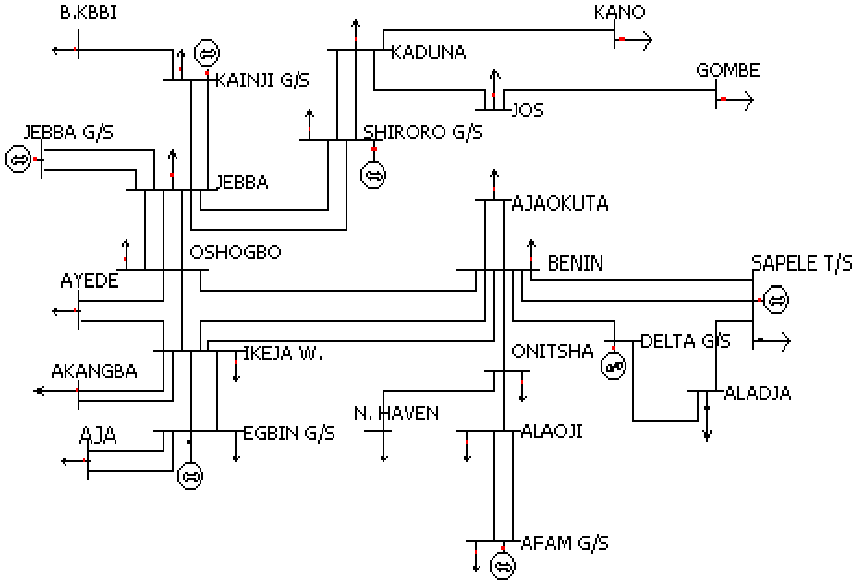

Fig. 5. A single line diagram of the Nigerian 330kV power system (Fasina et al, 2020).

3.2 Data Collection: The data used for this study were obtained from Power Holding Company of Nigeria (PHCN) and are presented in Table 1, Table2 and Table3.

TABLE 1. Line data (Fasina et al, 2020).

From Bus	To Bus	R (p.u)	X (p.u)
Osogbo	Ikeja	0.0099	0.0745
Osogbo	Benin	0.0098	0.0742
Egbin	Aja	0.0006	0.0044
Ikeja	Akangba	0.0007	0.0050
Osogbo	Ayede	0.0045	0.0340
Ikeja	Egbin	0.0023	0.0176
Ikeja	Benin	0.0110	0.0828
Ikeja	Ayede	0.0054	0.0405
Benin	Delta	0.0043	0.0317
Benin	Sapele	0.0020	0.0148
Kainji	Jebba	0.0032	0.0239
Shiroro	Kaduna	0.0038	0.0284
Afam(iv)	Alaoji	0.0010	0.0074
Ajaokuta	Benin	0.0077	0.0576
Jebba	Osogbo	0.0061	0.0461
Kaduna	Kano	0.0090	0.0680
Kaduna	Jos	0.0081	0.0609
Jos	Gombe	0.0118	0.0887
Sapele	Aladja	0.0025	0.0186
Benin	Onitsha	0.0054	0.0405
Onitsha	Newhaven	0.0036	0.0272
Delta(iv)	Aladja	0.0012	0.0089
Onitsha	Alaoji	0.0060	0.0455
Jebba GS	Jebba	0.0002	0.00020
JebbaTS	Shiroro	0.0096	0.0721
Kainji	Birnin	0.0122	0,0916

TABLE 2. Demand data (Fasina et al, 2021).

Bus No	Bus Name	P_{load} (MW)	Q_{load} (MVAR)
1	Sapele	21	15
2	Delta	0	0
3	Aja	274	206
4	Akangba	345	259
5	Ikeja	633	475
6	Ajaokuta	14	10
7	Aladja	97	72
8	Benin	383	288
9	Ayede	276	207
10	Osogbo	201	151
11	Afam	53	39
12	Alaoji	427	320
13	N-Haven	178	133
14	Onitsha	185	138
15	Birnin	115	86
16	Gombe	131	98
17	JebbaTS	11	8
18	JebbaGS	0	0
19	Jos	70	53
20	Kaduna	193	145
21	Kainji	7	5
22	Kano	200	150
23	Shiroro	320	256
24	Egbin	69	52

Table 3. Generator Data (Fasina et al, 2021).

Bus Name	Pg (MW)	Qg (MW)	Qgmax (MVAR)	Qgmin (MVAR)
Sapele	690	400	952	0
Delta	770	1407	3350	0
Afam	431	2155	9050	0
Jebba GS	495	1040	2475	0
Kainji	625	1312	3124	0
Shiroro	389	817	1945	0
Egbin	0	0	0	0

4. RESULT AND DISCUSSION

This section presents the result of load flow analysis using Newton Raphson iteration method. The analysis was based on 24-bus 330KV power transmission line in Nigeria used as a case study. Taking into consideration IEEE standard acceptable limits of ±10% tolerance.

4.1 POWER FLOW SOLUTION BY NEWTON RAPHSON METHOD

The result of the power flow solution for the system under consideration is as presented in Table 4 and Table 5. Newton Raphson power flow analysis was carried out on the test case with and without the UPFC using MATLAB software because of the number of buses involved.

Table 4: Power flow solution without UPFC

Bus No	Bus Name	Voltage Magnitude	Angle degree
1	Sapele	1.040	0.000
2	Delta	1.040	10.834
3	Aja	1.025	0.284
4	Akangba	1.012	0.640

5	Ikeja	1.018	1.068
6	Ajaokuta	1.036	6.162
7	Aladja	1.035	9.267
8	Benin	1.024	6.560
9	Ayede	**0.864**	**4.001**
10	Osogbo	1.013	6.650
11	Afam	1.040	10.314
12	Alaoji	1.0330	9.676
13	N-Haven	**0.856**	**4.522**
14	Onitsha	1.016	1.096
15	Birnin	1.033	13.893
16	Gombe	**0.825**	**5.376**
17	JebbaTS	1.034	12.357
18	JebbaGS	1.040	13.800
19	Jos	**0.872**	**9.265**
20	Kaduna	**0.862**	**7.011**
21	Kainji	1.040	15.558
22	Kano	**0.779**	**3.962**
23	Shiroro	1.040	8.075
24	Egbin	1.040	0.000

The result of power flow solution without UPFC incorporated shows that there are some buses like bus 9 (Ayede), 19 (Jos), 16 (Gombe), 22 (Kano), 13 (New heaven) and 20 (Kaduna) are having low voltages (i.e. below 0.94pu the allowable or permissible voltage limit) and was improved by applying UPFC in other to maintain the bus voltage magnitudes at 1.04 pu. The updated voltages are presented in the Table 5.

Table 5: power flow solution with UPFC

Bus No	Bus Name	Voltage Magnitude	Angle degree
1	Sapele	1.040	0.000
2	Delta	1.040	10.834
3	Aja	1.025	0.284
4	Akangba	1.012	0.640
5	Ikeja	1.018	1.068
6	Ajaokuta	1.036	6.162
7	Aladja	1.035	9.267
8	Benin	1.024	6.560
9	Ayede	**1.020**	**5.001**
10	Osogbo	1.013	6.650
11	Afam	1.040	10.314
12	Alaoji	1.0330	9.676
13	N-Haven	**1.021**	**9.615**
14	Onitsha	1.016	1.096
15	Birnin	1.033	13.893
16	Gombe	**1.010**	**11.442**
17	JebbaTS	1.034	12.357
18	JebbaGS	1.040	13.800
19	Jos	**1.031**	**18.262**
20	Kaduna	**1.032**	**12.011**
21	Kainji	1.040	15.558
22	Kano	**1.010**	**11.252**
23	Shiroro	1.040	8.075
24	Egbin	1.040	0.000

5. CONCLUSIONS

The growing demand for electricity due to population increase and industrialization without a corresponding increase in generation has resulted in system instability. In this paper, the power flow analysis of Nigerian 330kv grid system was carried out with and without incorporation of UPFC. The results show the weak buses which are found in the northern part of the country. The incorporation of UPFC in the power system provided improvement to the voltage instability at the weak buses. Unified power flow controller (UPFC) is a modern control equipment to control the real and reactive power flow on transmission lines either simultaneously or separately. Therefore, it is strongly recommended that the Nigeria power utility has to consider the use of Unified Power Flow Controller (UPFC to improve the network voltage and reduce voltage losses across the line in the system.

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