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Power Factor Control at Aba Control 33/11kV Injection Substation Using Auto Tuning Regulator

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Abstract-*Reactive Power Control, Voltage regulation and stability are very important for the efficient operation of the power system. This paper presents an auto- tuning regulator to enhance the performance of the Static Var Compensator at Aba Control 33/11kV Injection Substation. The controller was designed to adapt to operational dynamics of the substation, and promptly react to offset disturbances. Central Load compensation is used as it provides for more accurate and economical load compensation. The Auto-tuning regulator was designed using a Proportional – Integral – Derivative (PID) controller. It tunes automatically, following a deviation between the set and measured values. The power flow analysis of the substation was done using PSAT software. A compensation capacity of 15MVAr was implemented and the power factor was maintained at 0.96. The real and reactive power losses before compensation were 1.572p.u and 3.7525 respectively, but reduced to 0.1356p.u real power and 0.65237p.u reactive power after compensation. A less than 10% Voltage regulation was maintained across the buses.*

Keywords: **Power factor, PID Controller, Injection Substation, Auto–tuning, Regulator, Auto–tuning.**

1. INTRODUCTION

The power distribution System is characterized by loads which can be grouped as Residential, Commercial and Industrial Loads. The load and devices are mostly nonlinear, and as such, they injected harmonics into the system [1]. The distortion of current and/or voltage waveforms can lead to various power quality problems such as; poor power factor, low voltage profile, Voltage swells and sags [2]. Voltage level, frequency and waveform are the characteristics of electricity supply voltage. Although certain equipment can function when values deviate from the nominal range, efficiency and performance cannot be guaranteed. For equipment optimal performance, the voltage level, frequency and waveform must be within the nominal range [3]. Poor power quality can reduce the efficiency of connected equipment and increase the risk of damage. To ensure quality power supply, electricity must be supplied with voltage characteristics within nominal values, and with a limited number of interruptions. System recovery from a disturbance should be quick enough to avert prolonged interruptions and system collapse. At light load conditions, the distribution transformer output voltage is set by the On-Load Tap Changer (OLTC). As the load increase, this voltage begins to drop further away from the transformer, as the load current interacts with the impedance of the supply system.

The load type- resistive, capacitive or inductive affects the voltage profile of the network. Load across the distribution network are characteristically inductive, resulting in current lagging behind the voltage. This leads to an out of phase condition between the supply voltage and load current. The Total Power factor is actually a combination of Displacement and Distortion Power factors [3]. Poor power factor conditions result in severe power loss in the network, as the supplied power is not effectively used.

Shunt Capacitors have been used to improve displacement power factor, and filters have been installed to reduce distortion power factor [4]. To avert long interruptions and the improve accuracy of reactive power compensation; the constant gain and static controller are replaced with adaptive controllers. This leads to increased compensation accuracy, faster response time, reduced signal overshoot and faster settling time. An Adaptive controller was proposed in [5]. This paper presents the outcome of its implementation at the Aba 33/11kV Injection Substation, for reactive power compensation, and power factor control.

The Aba Control 33/11kV Injection substation, presented in Fig. 1, is a radial distribution substation having its feeders across a large area of the city of Aba. It is the major source of power supply within the city of Aba. It takes its supply from the Transmission Company of Nigeria (TCN), 132/33kV substation, and feds major areas of the city. The need for a stable and reliable power supply at the Aba Injection substation is very important, as power outages suffered at this substation affects the entire city of Aba, resulting in major blackouts across the city. This work paper seeks to reduce power loses as a result of power factor. The concept is adapting to power system dynamics while localizing the demand and supply of reactive power at the load bus. The network has a lot of suppressed load, as the available power supply is far below network requirement. The network is currently operating at average power factor of 0.82 and voltage profile falls as low as 9.3kV. This results in massive load reduction to prevent the network from collapse.

From Fig. 1, the substation has five primary 11kV feeders delivering power across the city. The network has a total of 319 transformers. Table 1 presents a summary of transformers across the network.

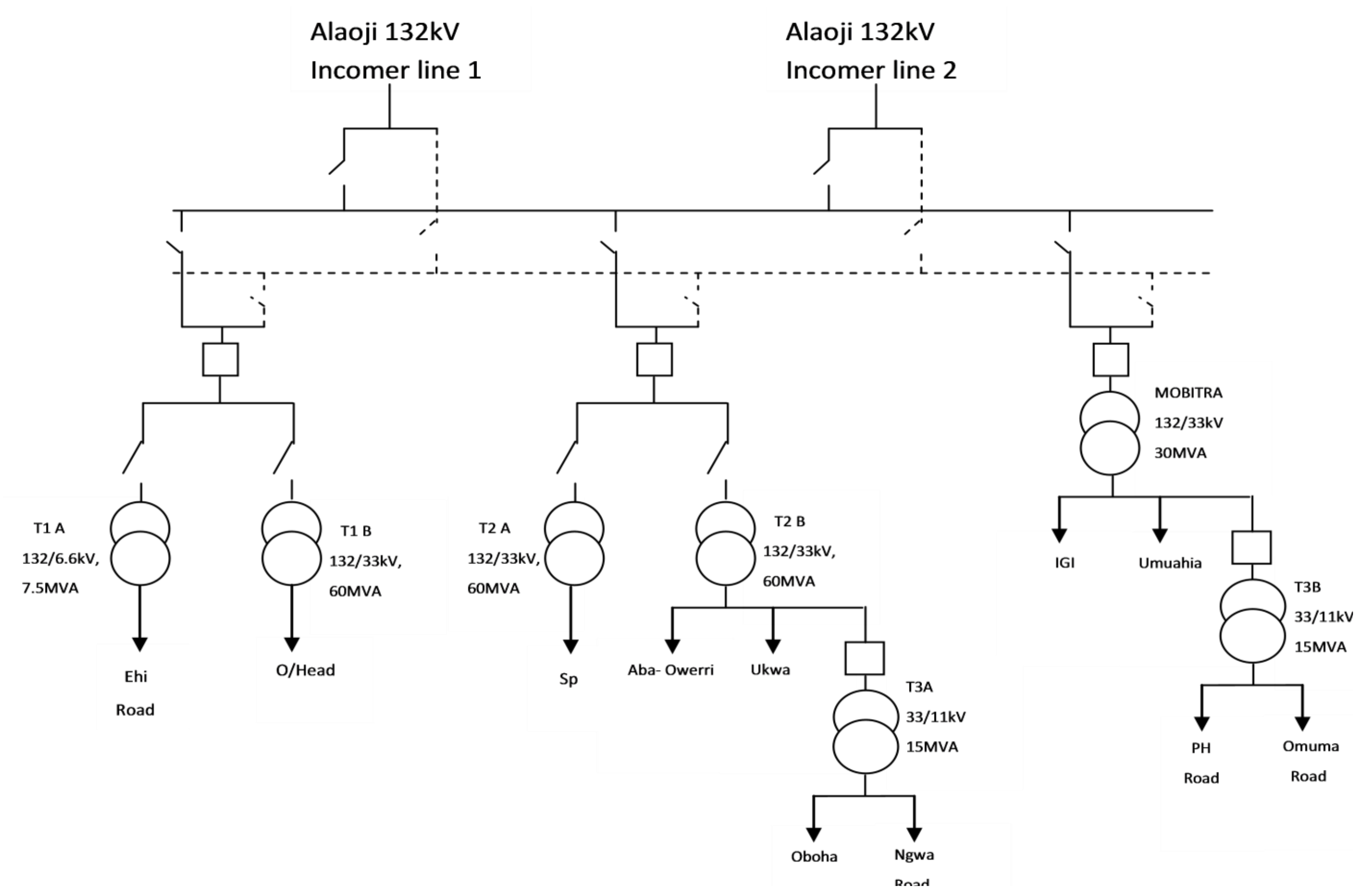
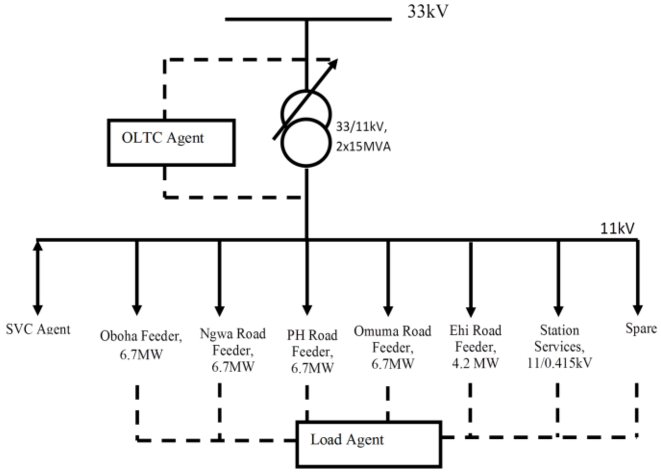


Fig. 1: Single line Diagram of Aba Control Substation

Table 1: Summary of transformers across the network

Feeders	Number of 300kVA Transformers	Number of 500kVA Transformers	Total Number of Transformers
Ehi Road-6.6kV	13	7	20
Oboha 11kV	32	18	50
Ngwa Road 11kV	69	20	89
Ph. Road 11kV	77	12	89
Omuma Road 11kV	52	19	71

Per unit (pu) values of data are used as it was very difficult to determine the actual length of these feeders [7].The control architecture presented in this paper includes On-load tap changer Agent, Load Agent, Static Var Compensator Agent and the co-ordination between these agents as presented in Fig. 2. In [8], details were given on the coordinated control between the On-Load Tap Changer OLTC, Static Var Compensator (SVC) and Load agents. The use of an Intermediate agent was introduced. The intermediate agent houses the control algorithm of the controller and is responsible for the coordinated control of the controller. The on-Load Tap Changer (OLTC) in conjunction with the Automatic Voltage Regulator (AVR) regulates the utility incomer voltage supply based on 17-step 1.25% setting. This helps to improve the voltage and maintain its value to as close as possible to nominal value [9]. The SVC injects or consumes Vars when the voltage profile across the bus depreciates to values beyond what the OLTC can handle or when the number of operations of the OLTC is exhausted. The Load Agent is not involved in voltage regulation but is implemented as an under-frequency load shedding scheme. This is included, as consideration is made as regards load profile growth without corresponding capacity expansion. This will eventually lead to system overload. The Load Agent is activated when all the stages of the capacitor banks are online without the network profile recovering. Based on priority table predetermined, the feeders are taken out and in as the network demands.



2. REVIEW OF RELATED WORKS

In [10], the use of Genetic Algorithm and ETAP for optimum location of SVC on a distribution system was proposed. Loses reduction, Active power transfer and voltage profile improvement were investigated. The results show a considerable reduction in loses, increased active power transfer capabilities, and improved voltage profile. But the performance was not considered. The impact of the number of SVC installed at various locations in a distribution network was investigated in [11]. The paper proposed the installation of two SVC at different locations as it gives better results in voltage stability, increased power transfer capabilities. Fitness of the buses was checked using Genetic Algorithm. Compensation Capacity and controller performance characteristics were not considered. [12] Proposed four control strategies for the SVC. Control strategies 1, 2 & 3 were designed to operate as open loop control systems while the fourth control strategy operated as closed loop control system. The design combined components like logic gates, flip flops, delay circuits, compensated gains, and op-amps. It aimed to balance voltage at the busbar based on these control strategies [13] Proposed a compensation technique based on alienation coefficient. It calculated the system power factor online and determined the size of capacitor banks required for optimal compensation. The proposed scheme recorded the following result:

- Ability to measure Phase voltage and line-current measurements at power supply.
- Ability to calculate current power factor on-line and acts as a power factor meter.
- It is simple, fast, reliable and accurate and can be implemented practically.

Essentially, all the works reviewed above are implemented in generic terms and not specifically for the distribution systems.

3. MATERIALS AND METHODOLOGY

3.1 Objective

The main objective of this paper is to implement reactive power compensation at Aba Control 33/11kV Injection Substation using Static Var Compensator and a dynamic controller. It is intended to improve power factor as it provides optimal compensation while increasing the network capacity release. Network variables such as real and reactive power flowing in each line, voltage magnitude and angle across each bus are considered.

3.2 Design Specifications

The control design specifications are given below;

- Increased Capacity release
- Reduced losses and
- Maintain power factor ≥ 0.96
- Voltage regulation ≤17%

4. DESIGN CALCULATIONS AND MATHEMATICAL MODELS

Parameters were calculated to determine the compensation requirement of Aba Control 33/11kV Injection Substation.

4.1 Compensation Capacity

In order to determine the size of compensation required, the operating power factor of the substation, desired power factor and network MVA rating must be known. [14] gives a quick guide to determine compensation capacity.

Operating power factor = 0.82, Desired power factor = 0.95, Network Capacity = 30MVA

From [14], the multiplier that corresponds to an operating power factor of 0.82 and desired power factor of 0.95 is 0.369

Therefore, required compensation capacity is $0.369\ X\ 30MVA = 11.07MVAr$

This is the minimum capacity of compensation required to attain a power factor of 0.95. This paper proposes a 15MVAr compensation to accommodate load growth.

4.2 SVC Component rating

The Transformer reactance,

$$X_{Tr1} = \frac{U_{z\%} * U_n^2}{100 * S_{Tr1}} \qquad (1)$$

.Network data:

- Bus voltage: 11kV
- The TCR is delta connected to the 11kV bus
- Associated Transformer rating: 15MVA, 33/11kV with Xk =15%

i. At rated line-to-line voltage (Urated), the nominal inductive and capacitive currents of SVC referred to primary side are determined as follows:

$$I_{C,rated} = \frac{Q_{c,rated}}{\sqrt{3}U_{rated}} = \frac{3x5x10^6}{\sqrt{3}x33x10^3} = 263A$$

$$I_{L,rated} = \frac{Q_{c,rated} - Q_{TCR}}{\sqrt{3}U_{rated}} = \frac{(3x5x10^6) - 6.3X10^6}{\sqrt{3}x33x10^3} = 151.6A$$

ii. At maximum line-line voltage

Umax = 36kV

$$I_{L,max} = I_{L,rated}\,x\frac{U_{max}}{U_{rated}} = 151.6\,x\frac{36\,x10^3}{33\,x10^3} = 165.38A$$

iii. At minimum line-line voltage

$$I_{C,min} = I_{C,rated}\,x\frac{U_{min}}{U_{rated}} = 263\,x\frac{30\,x10^3}{33\,x10^3} = 1239.09A$$

iv. The reactance of the TCR and FC, referred to the secondary side of the transformer

$$X_{L,rated} = \frac{U^2{}_{rated}}{Q_{L,rated}} = \frac{(11x10^3)^2}{6.3x10^6} = 19.20\Omega$$

$$X_{transformer} = 0.15\,x\frac{U^2{}_{rated}}{P_{transformer}} = 0.15x\frac{(11x10^3)^2}{15x10^6} = 1.21\Omega$$

$$X_{L,TCR}(\Delta) = X_{L,rated} - X_{transformer} = 19.20 - 1.21 = 17.99\Omega$$

$$X_{L,TCR}(1\Phi) = 3x17.99 = 53.97\Omega$$

$$L_{TCR} = \frac{53.97}{2x\pi x50} = 0.172H$$

$$X_{C,rated} = \frac{U^2{}_{rated}}{Q_{C,rated}} = \frac{(11x10^3)^2}{3x5x10^6} = 8.07\Omega$$

$$C = \frac{1}{2x\pi x50x8.07} = 0.395mF$$

From the calculations above, an SVC rating of: Qc =3x5$MVAr$, QTCR =6.3 $MVAr$ is installed.

4.3 Mathematical Models

The power flow analysis is used to determine the steady state performance characteristics of the substation. The following equations and models are presented for the purpose of simulation and analysis of the network. The network branch model is presented in Fig.3.

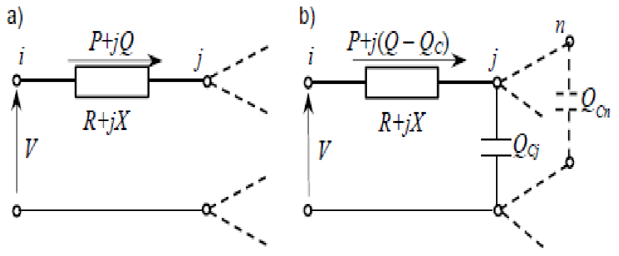


Fig. 3: Power flow in the network branch: a) without power factor correction: b) with the capacitors installed at nodes *j*, *j*+1,...,*n*. [15]

The following equations for loss reduction calculation across the network are presented in [15].

(a) Active Power loss in the branch before compensation is presented as:

$$\Delta P = \frac{P^2+Q^2}{V^2} * Z \qquad (2)$$

(b) Active Power loss after compensation, Q_C

$$\Delta P_C = \frac{P^2+(Q-Q_C)^2}{V^2} * Z \qquad (3)$$

Reduction in Power loss in branch ij is the difference of losses before and after compensation.

$$\delta P = \Delta P - \Delta P_C = \frac{Q_C^2 - 2QQ_C}{V^2} * Z \qquad (4)$$

Where: V- voltage across the bus, Q_C – Compensation provided, Z - Impedance

As load varies with time across the network, assuming a constant voltage, total energy loss over time, t is presented in [15] as:

$$\delta E_a = \int_0^t \delta P(t)\,dt = \frac{Z}{V^2}\int_0^t (Q_C^2 - 2Q(t)Q_C)dt \qquad (5)$$

Differentiating (14) gives;

$$\delta E_a = \frac{R}{V^2}(2E_rQ_C - Q_C^2T) \qquad (6)$$

Where: $\int_0^t Q(t)dt = reactiveenergy, E_r$

E_a = Active Energy

Equation (16) defines the maximum energy loss as;

$$Q_C^{opt} = \frac{E_r}{T} \qquad (7)$$

5. RESULT AND DISCUSSION

The Injection Substation was modeled and simulated using Matlab/Simulink Software for the purpose of analysis. The model is presented below.

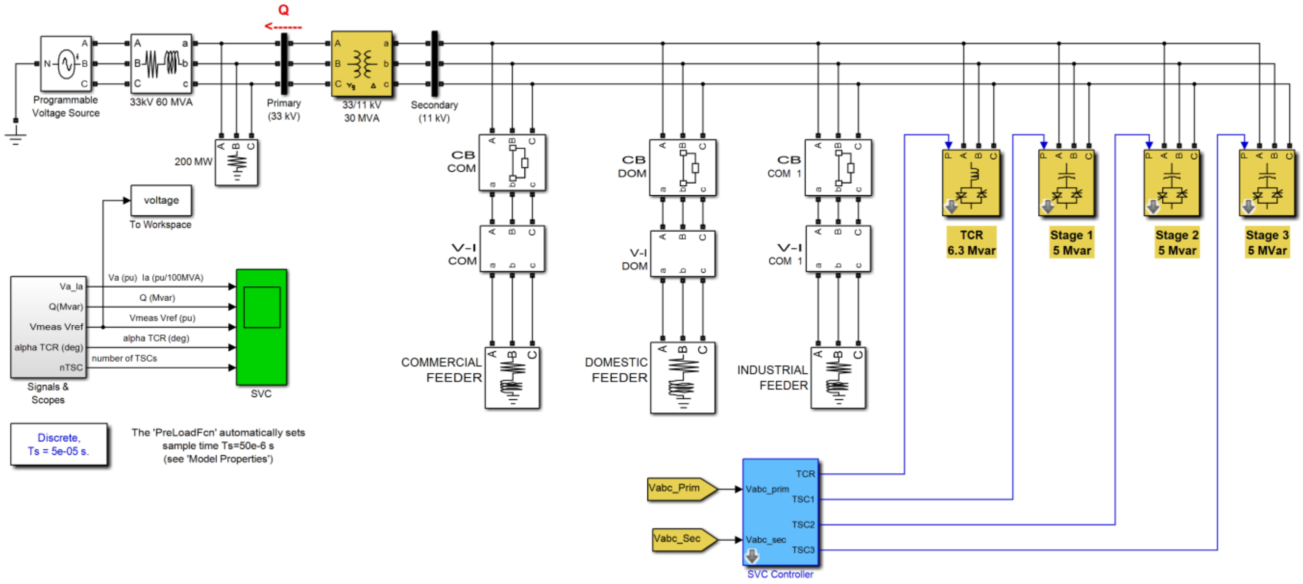


Fig. 4: Simulink Model of Aba Control Injection Substation Compensation

From Fig. 4, the feeders are grouped for the purpose of simplicity and ease of analysis as Commercial, Industrial and Domestic loads. Oboha and Omuma road feeders are considered in this paper as Domestic loads, PH road and Ngwa road feeders as Industrial loads, and Ehi road feeder as Commercial load. The network was simulated before and after compensation was implemented. The results are presented and discussed in the following paragraphs.

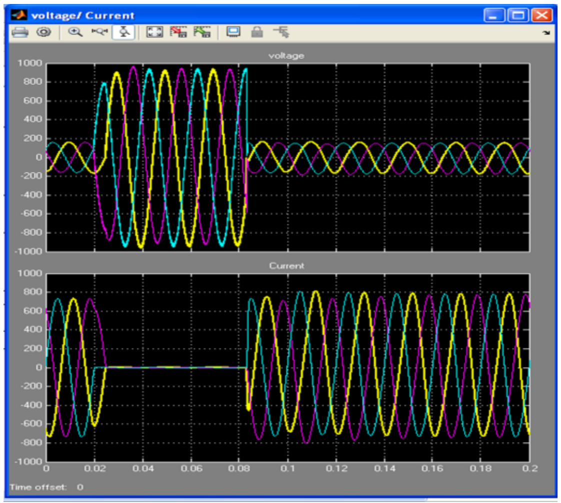


Fig.5: Current and voltage before compensation

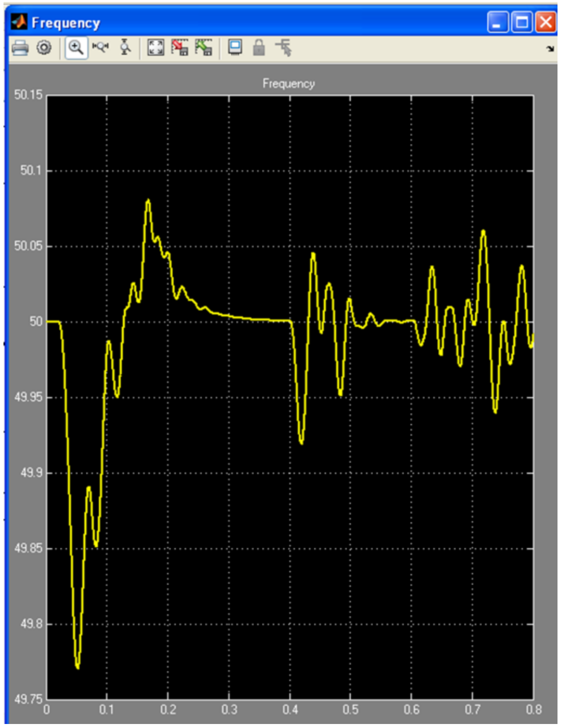


Fig.6: Frequency fluctuations before compensation

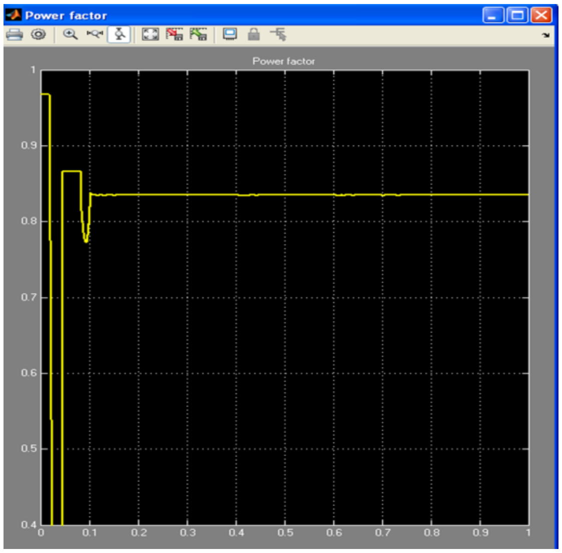


Fig.7: Power Factor before compensation

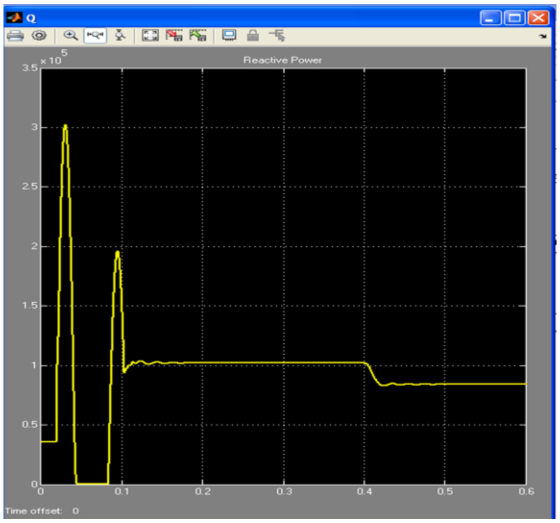


Fig.8: Reactive Power before compensation

Fig. 5 shows that load variations adversely affects the voltage of the network. The network is heavily stressed as load variations results to severe voltage swings. This condition can easily lead to system collapse if severe swings persist. Fig. 6 shows the erratic fluctuation of the frequency. Frequency fluctuations can have undesirable effect on the power system such as equipment damage, poor load performance, overloading of transmission lines, instability and interference with protection scheme of the substation. Operating Power factor is presented in Fig. 7. At light loads, the substation power factor was recorded to vary from 0.98 between 0 and 0.02s. As load increase, the power factor fluctuated and settled at 0.82. The system voltage was observed to have falling to 9.2kV. To maintain this value, several loads were suppressed. Fig. 8 shows a continuous absorption of reactive power by the loads. The adaptive controller was implemented and simulated using Matlab/Simulink software as presented in Figures 9 – 11.

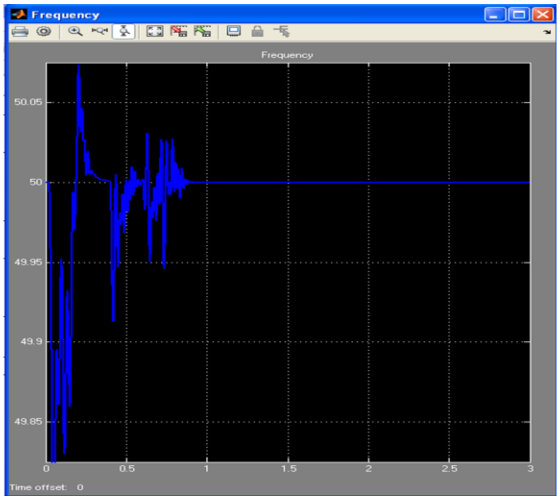


Fig.9: Frequency After compensation

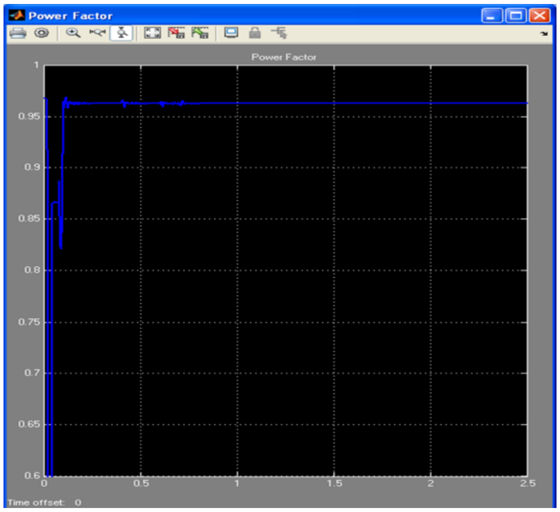


Fig.10: Power factor after compensation

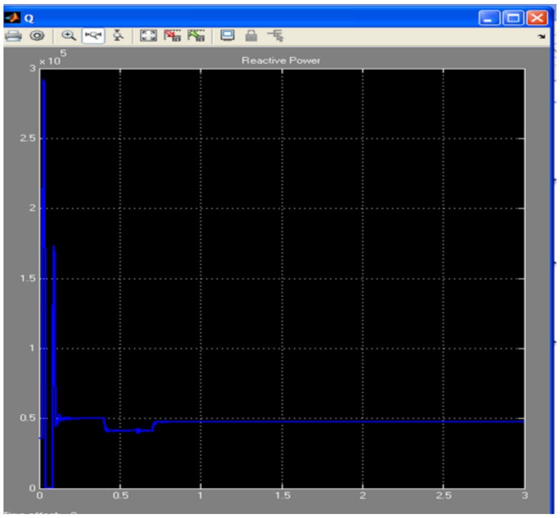


Fig.11: Reactive Power After compensation

Figures 9-11, show the system responses with the implementation of the SVC/ Adaptive controller technique. The substation experienced a disturbance as seen in the frequency fluctuation between 0 and 0.8s. the controller promptly reacted to normalize and maintain the frequency at 50Hz. The power factor was maintained at 0.96 while the reactive power supplied by the network was reduced and maintained at 0.005MVAr while the SVC injects or absorb the system VARs as required.

Using PSAT (Power System Analysis Tool) and data from Tables 2, and Newton Raphson's method for power flow studies was used to analyze the substation as presented in Fig.12.

This was done to investigate the effect of the controller and SVC on the voltages across the buses. The results are presented in Figures 13 and 14.

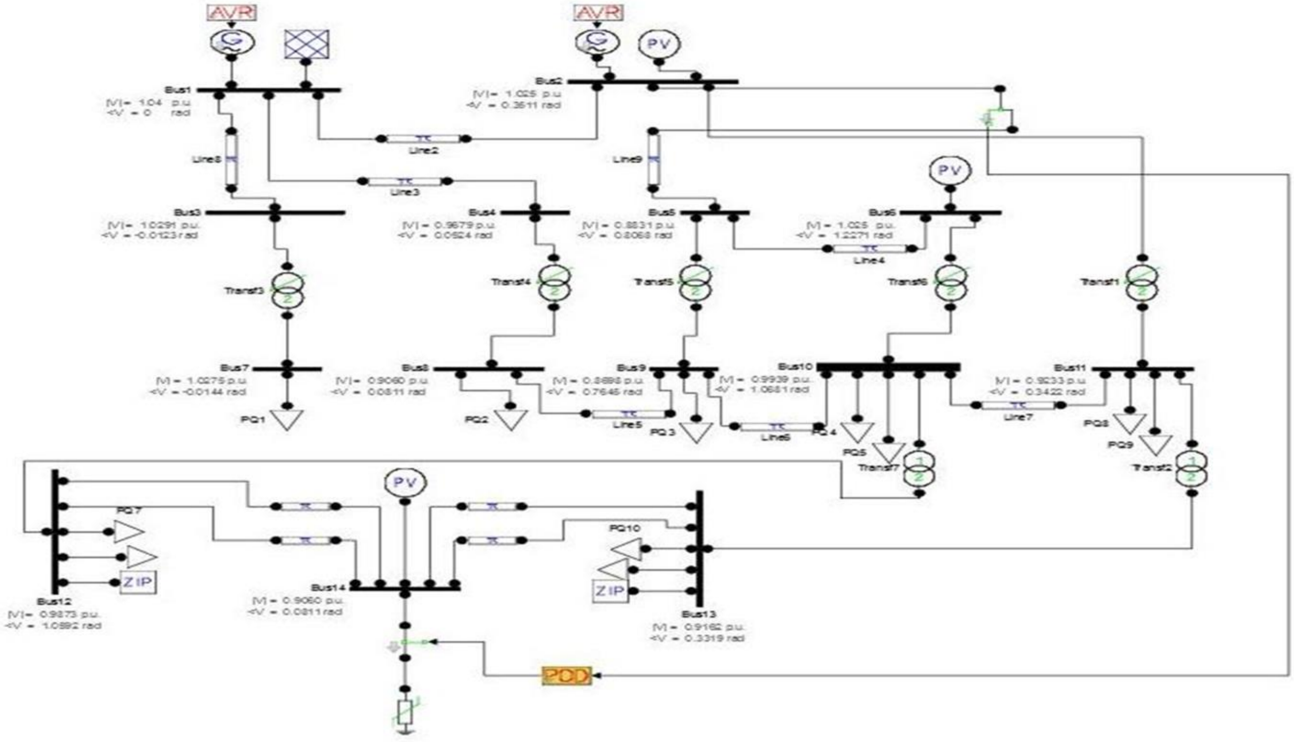


Fig. 12: Simulink model of Aba Control 33/11kV Injection Substation using PSAT

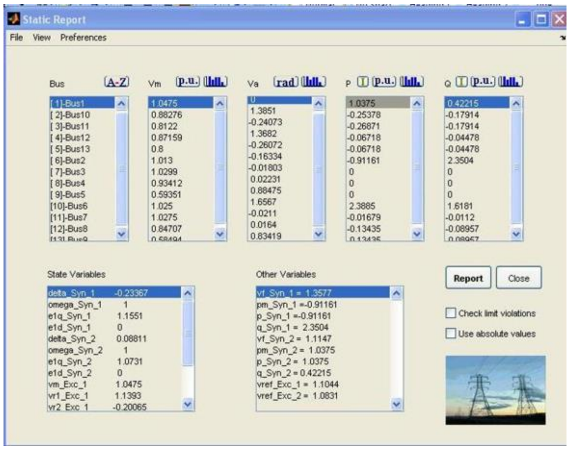
Table 2 presents the network data used in carrying out the simulation.

Table 2a: Generator data [13]

Generator bus no.	1	2	3	4	5
MVA	615	60	60	25	25
x_l (p.u.)	0.2396	0.00	0.00	0.134	0.134
r_a (p.u.)	0.00	0.0031	0.0031	0.0014	0.0041
x_d (p.u.)	0.8979	1.05	1.05	1.25	1.25
x'_d (p.u.)	0.2995	0.1850	0.1850	0.232	0.232
x''_d (p.u.)	0.23	0.13	0.13	0.12	0.12
T'_{do}	7.4	6.1	6.1	4.75	4.75
T''_{do}	0.03	0.04	0.04	0.06	0.06
x_q (p.u.)	0.646	0.98	0.98	1.22	1.22
x'_q (p.u.)	0.646	0.36	0.36	0.715	0.715
x''_q (p.u.)	0.4	0.13	0.13	0.12	0.12
T'_{qo}	0.00	0.3	0.3	1.5	1.5
T''_{qo}	0.033	0.099	0.099	0.21	0.21
H	5.148	6.54	6.54	5.06	5.06
D	2	2	2	2	2

Table 2b: Line Data

From Bus	To Bus	Resistance (p.u.)	Reactance (p.u.)	Line charging (p.u.)	KV	MVA
1	2	0.01938	0.05917	0.02640	132	200
1	3	0.05403	0.22304	0.02190	132	100
1	4	0.01355	0.04211	0.00640	132	100
2	5	0.05695	0.17388	0.01700	132	150
5	6	0.03181	0.0845	0	132	100
8	9	0.12711	0.27038	0	33	100
9	10	0.08205	0.19207	0	33	100
10	11	0.22092	0.19988	0	33	100



Bus	Vm	Va	P	Q
[1]-Bus1	1.0475	0	1.0375	0.42215
[2]-Bus10	0.88276	1.3851	-0.25378	-0.17914
[3]-Bus11	0.8122	-0.24073	-0.26871	-0.17914
[4]-Bus12	0.87159	1.3682	-0.06718	-0.04478
[5]-Bus13	0.8	-0.26072	-0.06718	-0.04478
[6]-Bus2	1.013	-0.16334	-0.91161	2.3504
[7]-Bus3	1.0299	-0.01803	0	0
[8]-Bus4	0.93412	0.02231	0	0
[9]-Bus5	0.59351	0.88475	0	0
[10]-Bus6	1.025	1.6567	2.3885	1.6181
[11]-Bus7	1.0275	-0.0211	-0.01679	-0.0112
[12]-Bus8	0.84707	0.0164	-0.13435	-0.08957
[13]-Bus9	0.58494	0.83419	0.13435	0.08957

State Variables

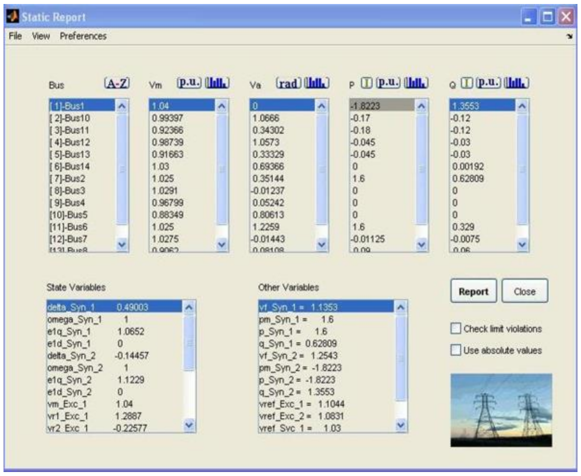
delta_Syn_1	-0.23367
omega_Syn_1	1
e1q_Syn_1	1.1551
e1d_Syn_1	0
delta_Syn_2	0.08811
omega_Syn_2	1
e1q_Syn_2	1.0731
e1d_Syn_2	0
vm_Exc_1	1.0475
vr1_Exc_1	1.1393
vr2_Exc_1	-0.20065

Other Variables

vf_Syn_1 = 1.3577
pm_Syn_1 =-0.91161
p_Syn_1 =-0.91161
q_Syn_1 = 2.3504
vf_Syn_2 = 1.1147
pm_Syn_2 = 1.0375
p_Syn_2 = 1.0375
q_Syn_2 = 0.42215
vref_Exc_1 = 1.1044
vref_Exc_2 = 1.0831

☐ Check limit violations
☐ Use absolute values

Fig. 13: Static power flow report for Uncompensated Aba 33/11kV Injection substation



Bus	Vm	Va	P	Q
[1]-Bus1	1.04	0	-1.8223	1.3553
[2]-Bus10	0.99397	1.0666	-0.17	-0.12
[3]-Bus11	0.92366	0.34302	-0.18	-0.12
[4]-Bus12	0.98739	1.0573	-0.045	-0.03
[5]-Bus13	0.91663	0.33329	-0.045	-0.03
[6]-Bus14	1.03	0.69366	0	0.00192
[7]-Bus2	1.025	0.35144	1.6	0.62809
[8]-Bus3	1.0291	-0.01237	0	0
[9]-Bus4	0.96799	0.05242	0	0
[10]-Bus5	0.88349	0.80613	0	0
[11]-Bus6	1.025	1.2259	1.6	0.329
[12]-Bus7	1.0275	-0.01443	-0.01125	-0.0075
[13]-Bus8	0.9062	0.08108	0.09	0.06

State Variables

delta_Syn_1	0.49003
omega_Syn_1	1
e1q_Syn_1	1.0652
e1d_Syn_1	0
delta_Syn_2	-0.14457
omega_Syn_2	1
e1q_Syn_2	1.1229
e1d_Syn_2	0
vm_Exc_1	1.04
vr1_Exc_1	1.2887
vr2_Exc_1	-0.22577

Other Variables

vf_Syn_1 = 1.1353
pm_Syn_1 = 1.6
p_Syn_1 = 1.6
q_Syn_1 = 0.62809
vf_Syn_2 = 1.2543
pm_Syn_2 = -1.8223
p_Syn_2 = -1.8223
q_Syn_2 = 1.3553
vref_Exc_1 = 1.1044
vref_Exc_2 = 1.0831
vref_Svc_1 = 1.03

☐ Check limit violations
☐ Use absolute values

Fig. 14: Static power flow report for Compensated Aba 33/11kV Injection substation

Summary Report for compensated and uncompensated network is presented in table 3.

NETWORK STATISTICS

Buses:	13
Lines:	8
Transformers:	7
Generators:	2
Loads:	7

The summary of the power flow analysis is presented in Table 3.

Table 3: Summary report of Power flow analysis

Parameter	Uncompensated Network		Compensated Network	
	Real Power	Reactive Power	Real Power	Reactive Power
Total Generation (p.u.)	2.5144	4.3907	4.6923	1.2357
Total Load (p.u.)	0.94234	0.63818	4.5567	-0.58333
Total Loss (p.u.)	1.572	3.7525	0.1356	0.65237

The uncompensated network has a total real and reactive power of 2.5144p.u. and 4.3907p.u. respectively. The system recorded an average power factor was 0.85. The network has a total loss of 1.572p.u. real power loss and 3.7525p.u. reactive power losses. With the addition of SVC, a total supply of 4.6923p.u. real power, 1.2357p.u. reactive power and loss of 0.1356p.u. real power loss and

0.65237 reactive power loss and the power was maintained at 0.96.

6. CONCLUSION

The results of the compensated and uncompensated Aba Control 33/11kV Injection substation as presented by the simulations shows that the real power loss reduced by 1.4354p.u. (91%) and reactive power loss reduced by 3.0988p.u.(82.5%). The steady state error is determined to be 0.17 at the point of connection of SVC. Therefore, Aba Control 33/11kV Injection performs better with increased capacity release, reduced loss and stabilized voltage across the bus when SVC is connected at the point of highest voltage swing.

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