INTERNATIONAL JOURNAL FOR INNOVATIVE RESEARCH IN MULTIDISCIPLINARY FIELD ISSN: 2455-0620 Volume - 5, Issue - 1, Jan – 2019
Monthly, Peer-Reviewed, Refereed, Indexed Journal with IC Value: 86.87 Impact Factor: 6.497 Publication Date: 31/01/2019

Design and Simulation of 20 MVAR Three Phase Shunt Reactor for Voltage Suppression at 230 kV Transmission Line (Kyaukpyu Primary Substation)

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Abstract: *In Myanmar, until recent years the reactive power compensations were commonly carried out by using shunt capacitors to increase the bus voltages. After the participation of Taungup and Ann power plants in national grid, the bus voltages of lower Myanmar become over voltages especially at light load. To suppress this power frequency over voltage and maintain at regulated voltage level, the shunt reactors become essential. Shunt reactors are mainly used to keep the voltage down, by absorbing the reactive power, in the case of light load and load rejection, and to compensate the capacitive load of the transmission line for reactive power balance. Shunt reactors are inductive loads similar to transformers but they are different than transformers in terms of construction and some electrical characteristics. Shunt reactors are widely deployed as effective compensation means against the capacitive behavior of high voltage transmission lines. In this paper, the design of 20 MVAR shunt reactor will be carried out for 230 kV Kyaukpyu primary substation. Simulation results will be provided by using Matlab/Simulink.*

Key Words: *Shunt Capacitors, Overvoltage Suppression, Shunt Reactor, Reactive Power Balance, Matlab/Simulink.*

1. INTRODUCTION:

In high voltage power system installations, inaccurate modelling of over voltages in the design and selection process can contribute to the equipment failure and service interruptions. This, in turn, not only disturbs the electrification process and reduces the reliability metrics but also increases the equipment maintenance and replacement costs. A precise understanding of over voltages mechanisms yields beneficial knowledge to contemplate effective precautions against the formation of these phenomena and to prevent the equipment major failures [1].

Besides, a highly reliable electrification system is achieved. Among different over voltages, the resonance and Ferro resonance phenomena are treated with a great importance in power system studies. Three main issues weight up such an importance. The first reason deals with permanent nature of these over voltages. Typically, they last for a long time on power system apparatuses rendering an increased insulation stress which intensifies the chance of equipment failure. The second point refers to the magnitude of these over voltages recorded to be much larger than the nominal operating voltages [1].

Normally, the equipment insulation cannot withstand such critical over voltages for a long time. The third issue speaks for unusual and hardly-predictable conditions which may stimulate resonance and Ferro resonance phenomena with a high occurrence probability. To establish a good knowledge of different occurrence conditions and avert the significant technical and economic losses, exact and thorough investigation of resonance over voltages seems essential.

One of the common cases which raise the probability of the resonance phenomenon in the grid is a double-circuit line compensated with a shunt reactor. Shunt reactors are usually used on high voltage transmission lines to limit over voltages during the line energization, load rejection, and under light load conditions [3].

However, upon the disconnection of one phase or line, the resonance can occur since the shunt reactors are fed through capacitive coupling from the adjacent phases or lines. If the resonance phenomenon is ignited, significant voltage drop is recorded over the whole line which not only threatens the equipment insulation but also saturates the magnetic core of the reactor. The core saturation comes with a decrement in reactor impedance and affects its operation conditions and characteristics. Moreover, the magnetic current of the reactor increases significantly accompanied with an enhancement in the flux density.

2. DESIGN AND OPERATION OF SHUNT REACTOR:

Shunt reactors are mainly used in transmission networks. Their function is to consume the excess reactive power generated by overhead lines under low-load conditions, and thereby stabilize the system voltage. They are quite often switched in and out on daily basis, following the load situation in the system. Shunt reactors are normally connected to substation bus bar, but also quite often directly to the overhead lines. Alternatively, they may also be connected to tertiary windings of power transformers. The shunt reactors may have grounded, or reactor grounded neutral [4].

Shunt reactors normally have iron cores with integrated air gaps. Due to the air gaps, the iron cores cannot be significantly saturated, and the reactors therefore will have a reasonably linear behaviour during energizing events, for example. Three-phase shunt reactors may consist of three separate single-phase cores, or they could be of three leg or five-leg design (alternatively shell type) as shown in Figure 1 and Figure 2.

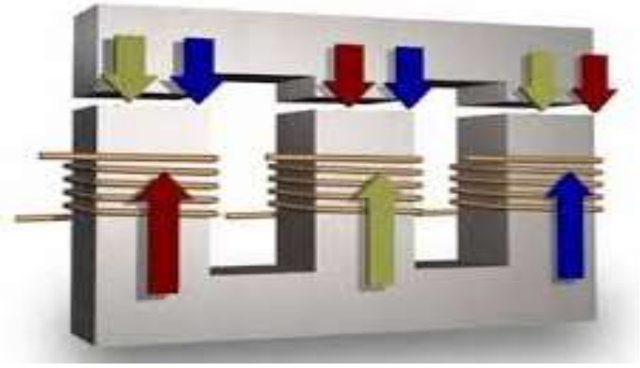

Figure 1: Three-leg Shunt Reactor Core

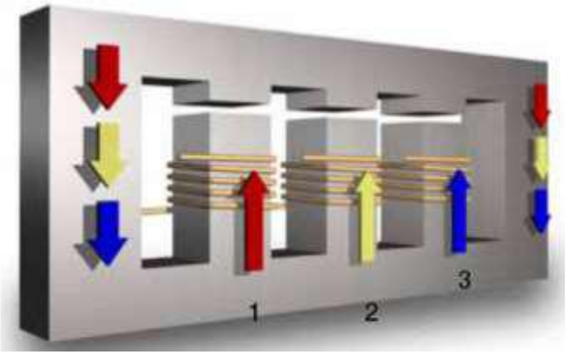

Figure 2: Five-leg Shunt Reactor Core with Three Wound Limbs [2]

For transmission voltages the Five-leg core type or shell type are mainly used. They make the three phases magnetically independent, while three-leg cores lead to magnetic coupling between phases.

Any significant period of one or two phase excitation necessitates the provision of a clearly defined return path for the zero-sequence flux created by the asymmetrical excitation. Where single phase operation is likely to occur, e.g. in power systems employing single pole auto-reclosing, there are two optional ways to achieve such a return path for the zero-sequence flux. These are:

- To use a three phase zero-limb core (or shell type core).
- To use single phase units.

One major advantage with a five leg reactor (or shell type) compared with a three leg reactor is that the construction to reduce vibrations and the long term use is much more stable and stronger. Medium voltage reactors, connected to tertiary windings of transformers, in most cases have air-insulated windings without iron cores [3].

3. THREE PHASE SHUNT REACTOR:

Three-phase shunt reactors are widely used in transmission and distribution networks. They absorb (consume) reactive power by connecting them to the transmission line. Since they decrease the voltage level, they are typically used during light load conditions. Shunt reactors are inductive loads that are used to absorb reactive power to reduce the over voltages generated by line capacitance. An inductive load consumes reactive power versus a capacitive load generates reactive power. A transformer, a shunt reactor, a heavy loaded power line, and an under magnetized synchronous machine are examples of inductive loads. Examples on a capacitive load are a capacitor bank, an open power line and an over magnetized synchronous machine. Although shunt reactors are inductive loads similar to transformers but they are different than transformers in terms of construction and some electrical characteristics [2].

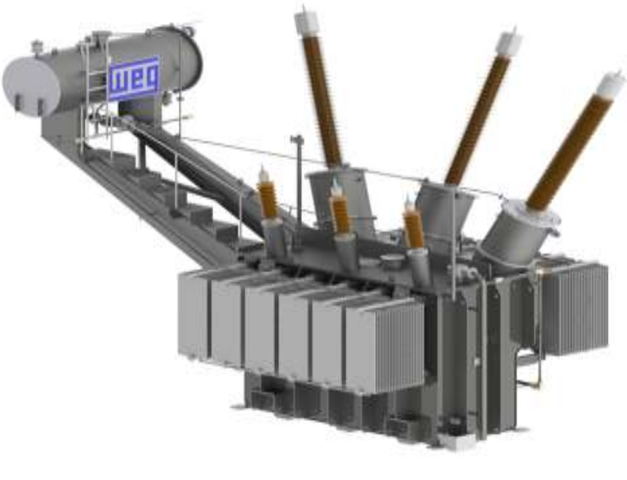

Figure 3: Three-phase Shunt Reactor

4. CLASSIFICATION OF SHUNT REACTOR:

Generally, there are two kinds of shunt reactors: dry-type reactors and oil insulated type reactors. Oil-immersed shunt reactors with an air-gapped iron core are widely used in transmission systems. For this type of reactor, the main winding and the magnetic circuit are immersed in oil. The insulation oil acts as the cooling medium, which can both absorb heat from the reactor winding and conduct the heat away by circulating the oil. The core of an oil-immersed reactor is made of ferromagnetic materials, with one or more built-in air gaps. These air gapped iron cores are designed to resist not only the mechanical stresses during normal operation but also withstand the fault conditions in the network.

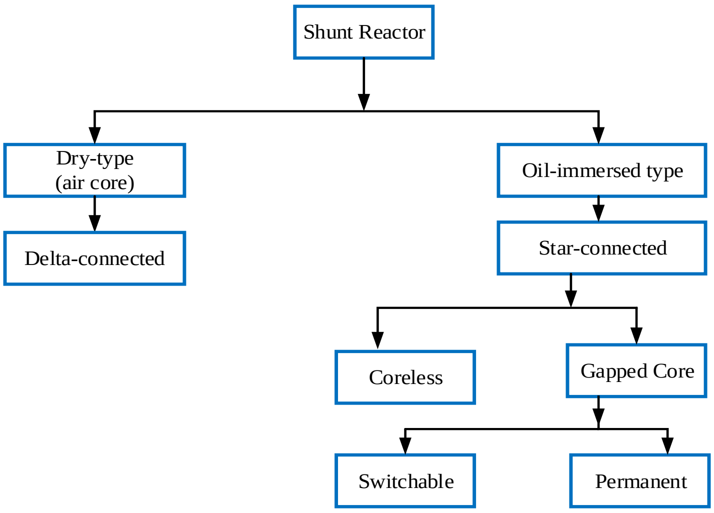

Figure 4: Classification of Shunt Reactor

The characteristic and design construction of shunt reactors are more dependent on the applied voltage. In Myanmar, 230 kV and 132 kV are referred to as transmission voltage network, whilst the distribution voltages are 33 kV, 11 kV, and 400 V. The design of shunt reactors rated 60 kV to 245 kV is most commonly oil-filled and have three-legged gapped cores with layer, continuous disc or interleaved disc windings. At 300 kV to 500 kV, the design of shunt reactors can be single-phase or three-phase units with three-legged, five-legged or shell-type cores.

Table I: Specifications of Three Phase Shunt Reactor

Rating	20 MVAR
Rated voltage	230 kV
Frequency	50 Hz
Number of phase	3
Winding Connection	YN (Star connected)
Type of Cooling method	Oil natural air natural (ONAN)
Type	Core type, cold-rolled silicon steel sheet
Location	Outdoor

5. DESIGN CALCULATION OF SHUNT REACTOR:

In order to design the magnetic frame based on the above specification, following design equations are needed.

5.1. Main Dimensions of Magnetic Frame

e.m.f equation, $E_1 = 4.44 f B_m A_i$

e.m.f per turn, $E_t = K\sqrt{\frac{\text{kVA}}{\text{phase}}}$

Cross section area of the core, $A_i = k_i d^2$

Output of shunt reactor, $Q = 3.33 f B_m \delta K_w A_w A_i$

Window area, $A_w = L(D-d)$

Gross yoke area, $A_y = 1.15 \times A_c$

Width of window, $b_w = D - d$

Width of yoke, $b_y = 0.9\,d$

Height of yoke, $h_y = \dfrac{A_y}{b_y}$

Gross core section, $A_c = \dfrac{A_i}{\text{Iron factor}}$

To utilize these design equations for calculating the main dimensions of the magnetic frame, suitable assumptions of various design parameters have been given below.

Table II: Suitable Assumptions of Various Design Parameters

Specifications	Symbol	Assumed value	Unit
Factor	K	0.65	-
Length of the flux path in the yokes	W	2.1258	m
Maximum flux density	B_m	1.5	Tesla
Ampere turns in core	at_c	170	AT
Ampere turns in yoke	at_y	100	AT
Flux density in core	B_c	1.5	Tesla
Core factor	k_i	0.75	-
Current density	δ	3	A/mm^2
Window space factor	k_w	0.24	-
Iron factor	-	0.95	-
Window proportion	$\dfrac{L}{D-d}$	4.5	-
Density of steel	-	7.55×10^3	kg/m^3

Table III: Calculation Results of Magnetic Frame

Specifications	Symbol	Calculated value	Unit
E.m.f per turn	E_t	53	V
Cross section area of the core	A_i	0.16	m^2
Diameter	d	0.462	m
Window area	A_w	0.695	m^2
Length of the core	L_c	1.7685	m
Width of window	b_w	0.393	m
Gross core section	A_c	0.1684	m^2
Gross yoke area	A_y	0.1937	m^2
Width of yoke	b_y	0.4158	m
Height of yoke	h_y	0.4658	m

To design the magnetic frame, mainly consider the type of magnetic material and have to calculate the iron losses called no load losses combination of iron losses of cores and yokes.

5.2. Iron Losses

The iron losses in the cores and yokes are mainly depended on the flux density used magnetic material.

Volume of cores, $V_c = 3 \times A_c \times L$

$$\text{Weight of cores, } W_c = V_c \times \text{Desity of steel}$$

$$\text{Iron losses in cores} = B_c \times W_c$$

$$\text{Volume of yokes, } V_y = 2A_y W$$

$$\text{Flux density of yokes, } B_y = 1.5 \times \frac{A_c}{A_y}$$

$$\text{Weight of yokes, } W_y = V_y \times \text{Density of steel}$$

$$\text{Iron losses in yokes} = B_y \times W_y$$

Table IV: Calculation Results of Iron Losses

Specifications	Symbol	Calculated value	Unit
Volume of cores	V_c	0.8936	m^3
Weight of cores	W_c	6746.3	kg
Iron losses in cores	-	10.12	kW
Volume of yokes	V_y	0.8235	m^3
Weight of yokes	W_y	6217.4	kg
Flux density of yokes	B_y	$1.3 \approx 1$	Tesla
Iron losses in yokes	-	6.2174	kW

Iron losses in cores and yokes = 10.12+6.2174

=16.3374 kW

The above value of iron losses is increased by 7% to take into account the effect of unequal flux density distribution in the core and yoke cross section, mechanical working of laminations and joints.

Total iron losses = 1.07 × 16.33643

= 17.48 kW

5.3. No Load Current

$$\text{Total amp-turns for 3 cores, } AT_c = 3 \times at_c \times L_c$$

$$\text{Total amp-turns for 2 yokes, } AT_y = 3 \times at_y \times L_y$$

$$\text{Total amp-turns, } AT = AT_c + AT_y$$

$$\text{Total amp-turn per phase} = \frac{AT}{3}$$

$$\text{Number of turns/phase in reactor, } T = \frac{V}{E_t}$$

$$\text{r.m.s value of magnetizing current, } I_m = 1.1 \times \frac{AT}{\sqrt{2} \times T}$$

$$\text{r.m.s value of no-load current, } I_w = \frac{\text{Total iron losses}}{\sqrt{3} \times \text{KVA}}$$

$$\text{No-load current per phase, } I_0 = \sqrt{I_m^2 + I_w^2}$$

$$\text{Current in reactor per phase, } I = \frac{\text{MVAR}}{\sqrt{3} \times \text{kVA}}$$

Table V: Calculation Results of No Load Current

Specifications	Symbol	Calculated value	Unit
Total ampere turns for 3 cores	AT_c	901.935	AT
Total ampere turns for 2 yokes	AT_y	425.16	AT
Total ampere turns	AT	1327.095	AT

Total ampere turn per phase	-	442.365	AT/ph
Number of turns/phase in reactor	T	1446	turn/ph
r.m.s value of magnetizing current	I_m	0.2379	A
r.m.s value of no-load current	I_w	0.044	A
No-load current per phase	I_0	0.242	A
Current in reactor per phase	I	50.2	A

$$\text{Percentage of no-load current} = \frac{I_0}{I} \times 100\%$$
$$= 0.4821\ \%$$

5.4. Losses of Designed Shunt Reactor

Total iron losses = 17.48 kW

Total copper losses = 34.914 kW

Winding connections and stray losses increase the copper losses, which is taken approximately 5%.

Total copper losses = 1.05 × 34.914 kW = 36.66 kW

Total losses at full load = 17.48 + 36.66

= 54.14 kW ≈ 55 kW

5.5. Efficiency of Shunt Reactor

$$\text{Efficiency of shunt reactor} = \frac{P_{out}}{P_{in}} \times 100\% = \frac{20000}{20000+55} \times 100\% = 99.7257\%$$

6. PERFORMANCE ANALYSIS OF SHUNT REACTOR IN KYAUKPYU PRIMARY SUBSTATION

In this substation, incoming voltages are up to within limit (+5%). So, 20 MVAR shunt reactor used for incoming voltages are within limit (±5%) in the stability region.

Table VI: 230 kV Incoming Line Voltages per Hourly Load without Shunt Reactor

Time	Voltage (kV)	Power (MW)	Power Factor	Current (A)
1:00	243	13.54	0.8	$41.53\angle -36.87^\circ$
2:00	245	13.39	0.8	$41.92\angle -36.87^\circ$
3:00	246	12.97	0.8	$40.00\angle -36.87^\circ$
4:00	246	13.80	0.8	$45.20\angle -36.87^\circ$
5:00	249	18.23	0.8	$54.24\angle -36.87^\circ$
6:00	246	18.15	0.8	$56.37\angle -36.87^\circ$
7:00	245	14.22	0.8	$42.69\angle -36.87^\circ$
8:00	245	12.71	0.8	$39.68\angle -36.87^\circ$
9:00	243	12.85	0.8	$35.97\angle -36.87^\circ$
10:00	245	17.23	0.8	$41.34\angle -36.87^\circ$
11:00	246	17.43	0.8	$40.74\angle -36.87^\circ$
12:00	242	21.75	0.8	$46.18\angle -36.87^\circ$
13:00	241	23.61	0.8	$53.71\angle -36.87^\circ$
14:00	243	25.28	0.8	$56.87\angle -36.87^\circ$
15:00	241	26.49	0.8	$57.83\angle -36.87^\circ$
16:00	245	19.78	0.8	$44.95\angle -36.87^\circ$
17:00	248	12.28	0.8	$31.53\angle -36.87^\circ$
18:00	249	16.04	0.8	$33.45\angle -36.87^\circ$
19:00	247	17.06	0.8	$36.02\angle -36.87^\circ$
20:00	246	19.29	0.8	$40.44\angle -36.87^\circ$

21:00	247	18.96	0.8	$40.94\angle-36.87^{\circ}$
22:00	246	17.96	0.8	$41.14\angle-36.87^{\circ}$
23:00	246	17.35	0.8	$42.67\angle-36.87^{\circ}$
24:00	247	15.36	0.8	$37.14\angle-36.87^{\circ}$

Incoming voltages of 230 kV bus are up to the limit 230+5% (241.5 kV) for Kyaukpyu substation as shown in Table VI. Maximum load is 26.49 MW at 3:00 p.m and minimum load is 12.28 MW at 5:00 p.m.

Resistance per phase of reactor, $R_{SR} = 3.74\,\Omega$

For three phase, $R_{SR} = 3\times 3.74 = 11.22\,\Omega$

Shunt reactance, $X_{SR} = 2\pi fL$

Shunt impedance, $Z_{SR} = R_{SR} + jX_{SR}$

Bus voltage, $V_{BUS} = \sqrt{3}\times\left(\frac{V_S}{\sqrt{3}} - (I_{BUS}\times Z_{SR})\right)$

Table VII: 230 kV Incoming Line Voltages per Hourly Load with Shunt Reactor

Time	Voltage (kV)	Power (MW)
1:00	238	13.54
2:00	239	13.39
3:00	241	12.97
4:00	240	13.80
5:00	242	18.23
6:00	239	18.15
7:00	239.7	14.22
8:00	240	12.71
9:00	238.5	12.85
10:00	239.8	17.23
11:00	240	17.43
12:00	236.2	21.75
13:00	234.3	23.61
14:00	235.9	25.28
15:00	233.83	26.49
16:00	239.4	19.78
17:00	241	12.28
18:00	241.5	16.04
19:00	241.3	17.06
20:00	240.9	19.29
21:00	241.4	18.96
22:00	240.8	17.96
23:00	240.7	17.35
24:00	241.2	15.36

Table VIII: Results of Voltage Regulation with Shunt Reactor

Time	Voltage Before Installation (kV)	Voltage After Installation (kV)	Voltage Regulation (%)
1:00	243	238	-2.1
2:00	245	239	-2.5
3:00	246	241	-2.07
4:00	246	240	-2.5
5:00	249	242	-3.75
6:00	246	239	-2.93
7:00	245	239.7	-2.21
8:00	245	240	-2.08

9:00	243	238.5	-1.88
10:00	245	239.8	-2.17
11:00	246	240	-2.5
12:00	242	236.2	-2.45
13:00	241	234.3	-2.86
14:00	243	235.9	-3
15:00	241	233.83	-3.06
16:00	245	239.4	-2.34
17:00	248	241	-2.9
18:00	249	241.5	-3.1
19:00	247	241.3	-2.36
20:00	246	240.9	-2.12
21:00	247	241.4	-2.32
22:00	246	240.8	-2.16
23:00	246	240.7	-2.2
24:00	247	241.2	-2.4

Figure 5: Comparison of Bus Voltage with and without 20 MVAR Shunt Reactor

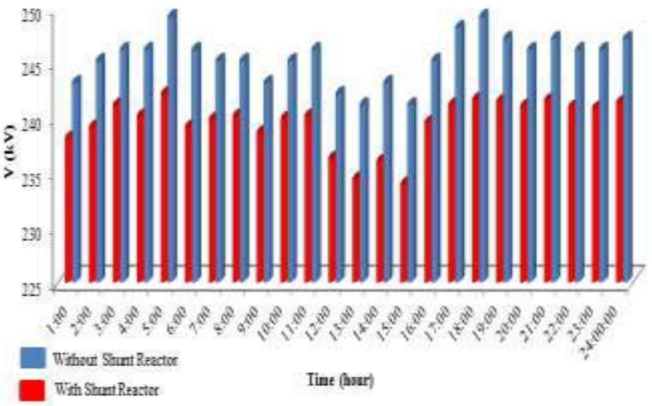

Figure 6: Results of Bus Voltage with and without 20 MVAR Shunt Reactor

7. SIMULATION OF SHUNT REACTOR IN KYAUKPYU PRIMARY SUBSTATION

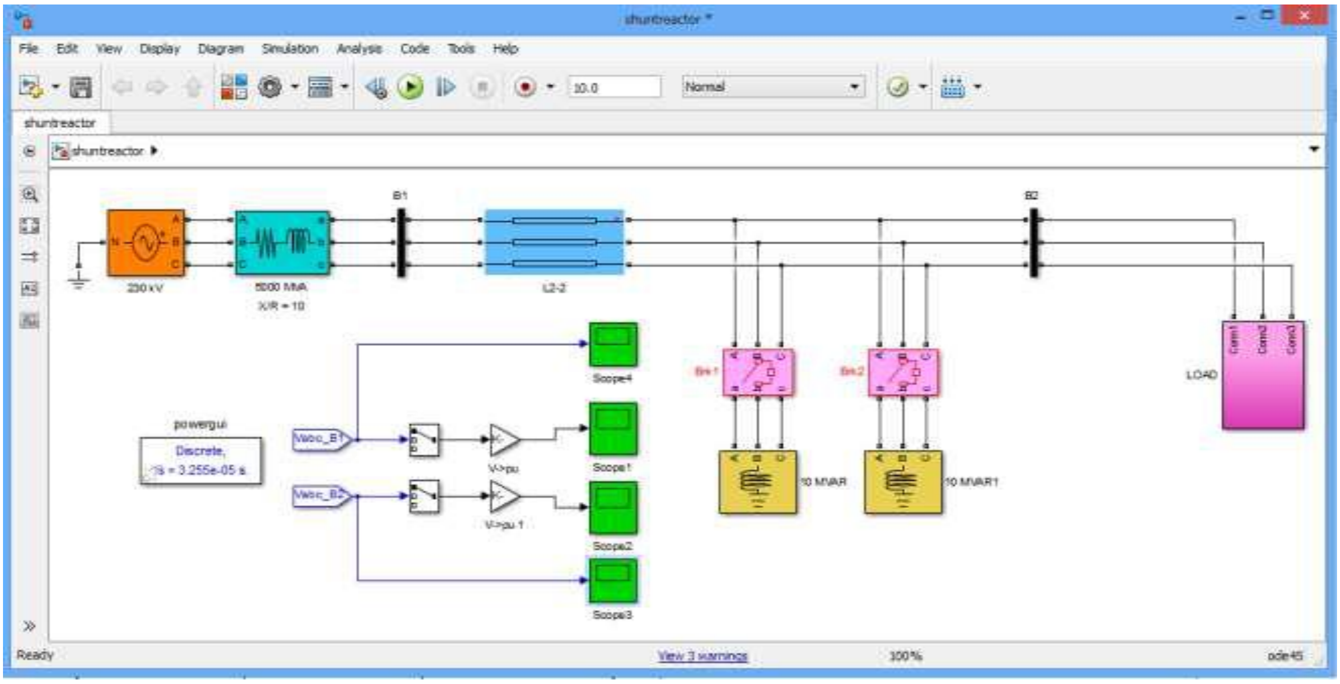

Figure 7: Simulink Model for Voltage Suppression Using 20 MVAR Shunt Reactor

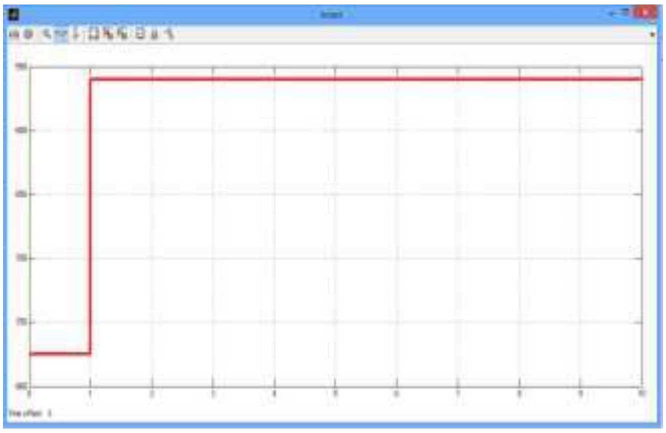

Figure 8: Simulation Results of Per Unit Voltage with 20 MVAR Shunt Reactor at Scope 1

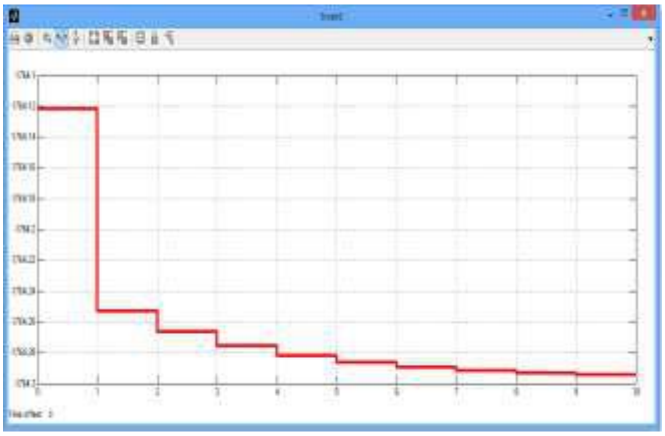

Figure 9: Simulation Results of Per Unit Voltage with 20 MVAR Shunt Reactor at Scope 2

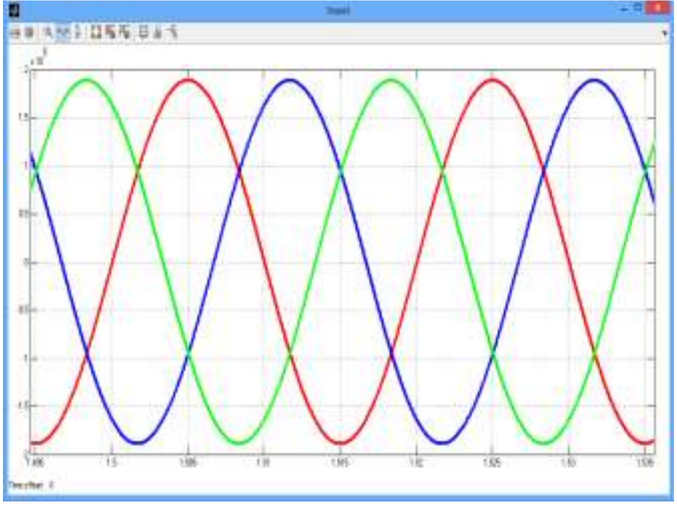

Figure 10: Bus Voltage with 20 MVAR Shunt Reactor at Scope 3

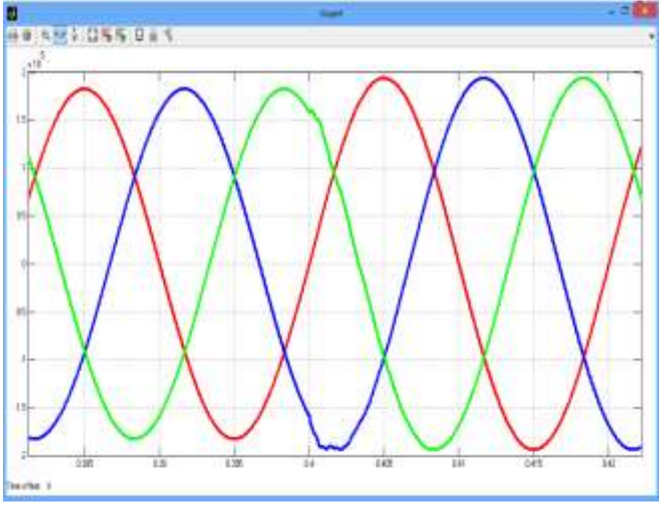

Figure 11: Bus Voltage with 20 MVAR Shunt Reactor at Scope 4

8. CONCLUSION:

The shunt reactor is the most cost efficient equipment for maintaining voltage stability on the transmission lines. Shunt reactor can be used as the voltage control device which is often connected directly to the high voltage lines. This paper presents interactive three-phase shunt reactor knowledge for the education of beginners and design engineers for electrical engineering field. These shunt reactors are can be useful in power system analysis, reactive power compensation, voltage stability and control. For 20 MVAR, 230 kV, three-phase, star-connected, core type shunt reactor is already designed. It can be used in transmission system and substations. This core-type shunt reactor is used to regulate the line voltage and to control within the voltage stability limit of ±5% for designing the core-type shunt reactor and it is important to study the available information in power system of Myanmar. Therefore, it can be said that the design of the core-type shunt reactor is one of the most important in electrical engineering field.

ACKNOWLEDGEMENT:

The author is grateful to express his gratitude to all persons who were directly or indirectly involved towards the successful completion of this paper.

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APPENDIX:

230 kV Kyaukpyu Primary Substation (One Line)