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Design of 25 MVA Shunt Reactor for 230 kV Transmission Line

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Abstract: In power system, the reactive power compensation is important for system voltage profile. This is also helpful to power factor improvement and loss reduction. 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 Yeywa and Shweli power plants in national grid, the bus voltages of upper Myanma 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. In this paper, the design of 25 MVA shunt reactor will be carried out for 230 kV Nyaungbingyi substation.

Keywords: Overvoltage Suppression, Shunt Reactor, Loss Reduction, Regulate Voltage Level, Reactive Power Balance.

I. INTRODUCTION

High voltage transmission lines have an inherent characteristic of self-producing capacitive reactive power along the length of the transmission line. This is due to the distributed nature of the charging current caused by shunt capacitance due to electrostatic field to earth. This is more evident and prevalent on the longer transmission lines. Also, When a long, lightly loaded, transmission line is open-circuited at the receiving end, line charging capacitance current flow through the line inductance thus voltage rise at the receiving end normally higher than sending end voltage. This results in the phenomenon that is called Ferranti Effect. Line reactors are therefore used to provide the counter action to this effect. Ferranti Effect arises as a result of capacitive coupling, load rejection, Ferro-resonance and unbalanced ground faults on the line. The voltage rise presents some problems to the utilities as power quality issues are often violated.

Higher voltages than rated steady-state voltages also increase the stress levels in the insulation of the network equipment which often leads to reduced life span of the equipment, Also, under light loading condition of the network, capacitive current that result from transmission line charging capacitance, exceeds the inductive current that flows in the system and that causes the voltages along the length of the line to increase. Such lines or networks are also prone to the voltage instability problems that arise as a result of the length of the line and the load that needs to be transmitted. Thus, shunt inductive reactive compensation is often required to suppress over voltages and absorb excess reactive power. Shunt line reactors have therefore been used in power systems around the world when the above mentioned conditions arise and they are of fixed type. Shunt reactors are primarily used in power systems to suppress over voltages in case of sudden rise or rapid fluctuations in system voltages. These conditions normally arise during switching of the network and also when a large load is suddenly lost, as in a case of load rejection. When these conditions arise, the voltage in the network rises and the line reactor is used to limit this voltage rise to within acceptable limits.

II. OVERVOLTAGE IN POWER SYSTEM

The voltage level along an AC transmission line is influenced by two main factors; the capacitive charging and the loading of the line. The capacitive charging, which is the source of reactive power generation (Q_C), depends on the line geometry and the line voltage level; and arises because of the capacitance between its conductors and the earth. On the other hand, when the line is loaded, both the load and the line consume reactive power(Q_L) as inductive electrical elements. In an AC transmission system, it is important to keep the balance between generated and consumed reactive power since it is the reactive power balance which decides the voltage stability of the line. In order to achieve the reactive power balance, the line should be loaded at its natural load where the generation and consumption of reactive power along the line are equal. When the load varies in the system, the consumption of reactive power changes, and consequently the voltage fluctuates along the line. If the generated reactive power is more than the consumed reactive power, the voltage increases, whereas the voltage decreases if the consumption is more than generation of reactive power.

A. Reactive Power and Voltage Control Service

Reactive power and voltage control service should satisfy power system requirements listed below:

- Satisfy overall system and customer requirements for reactive energy on a continuous basis;
- Maintain system voltages within acceptable limits;
- Provide a reserve to cover changed reactive requirements caused by contingencies, against which the system is normally secured, and satisfy certain quality criteria in relation to speed of response;
- Optimize system losses.

In reactive power and voltage control a distinction between three levels of voltage control could be made:

1. Primary control is implemented by the voltage regulators of generating units, which will initiate a rapid variation in the excitation of generators when they detect a variation in voltage across their terminals. Other controllable devices, such as static var compensators (SVCs) may also be involved in primary regulation.
2. Secondary control co-ordinates the action of voltage and reactive power control devices within a given zone of the network in order to maintain the requisite voltage level at a certain node point in the system.
3. Tertiary control involves a process of optimization, using calculations based upon real time measurements, in order to adjust the settings of devices, which influence the distribution of reactive power (generating unit controllers, tap transformer controllers and compensating devices, like reactors and capacitors).

Where the system load is high, the operator must be certain that, in case of a loss of generation, the remaining facilities will be able to deliver enough reactive power to keep the voltage within the required range. The same applies to the converse situation, where the system load is low and reactive power needs to be absorbed. Reactive power is produced or absorbed by all major components of a power system are generators, power transfer components, loads and reactive power compensation devices.

III. THREE-PHASE SHUNT REACTORS

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 (figure 1) are inductive loads similar to transformers but they are different than transformers in terms of construction and some electrical characteristics.

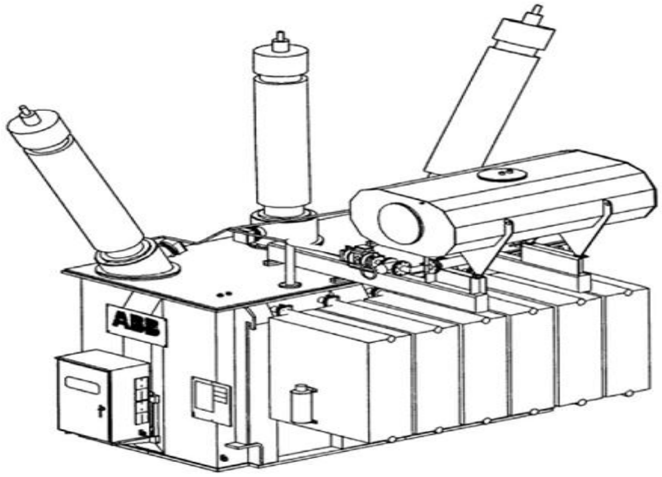

Figure1. Schematic of a three-phase shunt reactor.

IV. CLASSIFICATION OF SHUNT REACTORS

Figure2 shows the classifications of shunt reactors according to applications and design. 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.

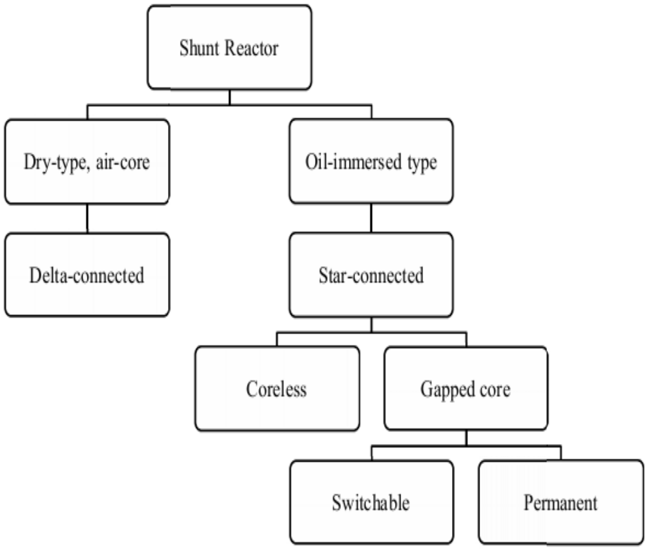

Figure 2. Classification of shunt reactors.

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. For shunt reactors rated below 60 kV, the design is either oil-filled three-legged iron core types or dry coil types. Depending on the intended function, a shunt reactor can be designed to have either linear or adjustable inductances. As the name implies, linear shunt reactors have constant inductance within the specified tolerances. Conversely, a shunt reactor in which the inductance can be adjusted by changing the number of turns on the winding or by varying the air gap in the iron core is called an adjustable shunt reactor. The number of turns on a winding is changed by means of a tap changer. The service conditions are vital to the design and structure of the shunt reactor. For oil-immersed shunt reactors, the ambient temperatures are usually specified within the range of -25°C to 40°C. Exceeding the specified ambient temperature may reduce both the reliability and the life of the shunt reactor. The shunt reactor is installed in a three-phase system as either a three-phase shunt reactor or three single-phase shunt reactors. Generally, single-phase shunt reactors are favored over three-phase shunt reactors due to cost benefits and transport restrictions.

V. SHUNT REACTOR CONNECTED TO BUSBAR

The reactors are normally connected to power system in three locations. These reactors can be connected to line, bus or tertiary winding of the power transformer or auto-transformer. In this design, 20 MVA three-phase shunt reactor is connected to 230 kV transmission line. Figure 3 shows a practical circuit used for simplified voltage control analysis in an electrical system. Upon the connection and disconnection of the shunt reactor, voltage variation at the high-voltage busbar should not be higher than 2-3% of the rated voltage. The reactor rating should be chosen to limit the magnitude of the voltage step change that occurs during a routine switching operation. Where, V_1 is the maximum bus voltage and V_2 is the acceptable bus voltage that should be maintained in the system. $S_{R3Ø}$ represents the required inductive power of the shunt reactor necessary to reduce the voltage level from voltage $V_1$to voltage V_2. It is noted that the power rating of the shunt reactor is merely dependent on the specified voltage limits and the short-circuit level of the compensated system.

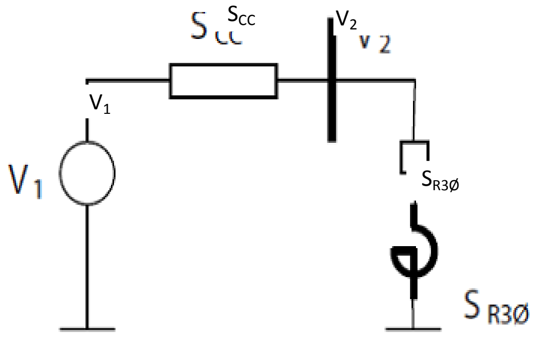

Figure 3. Circuit for voltage control analysis.

TABLE I: SPECIFICATIONS OF THREE-PHASE SHUNT REACTOR

Rated power	25 MVar
Rated voltage	230 kV
Rated current	62.8 A
Number of phase	3
Frequency	50 Hz
Connection symbol	YN
Percent tapping	±2×2.5%
Number of tapping	7 positions
Noise level	84.6 dB
Cooling method	ONAN
Max. ambient temperature	45°C
Winding temperature rise	60 K
Load losses at 75°C	95.7 kW
Rated reactance at 75°C	2691.51 Ω
Oil type	APAR TO 1020
Active part weight	12900 kg
Oil weight	18000 kg
Total weight	51000 kg
Type	Core type, cold-rolled silicon steel sheet
Location	Outdoor

VI. DESIGN OF SHUNT REACTOR

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 behavior during energizing events. Three-phase shunt reactors may consist of three separate single-phase cores, or they could be of three-leg (core type), shown in Figure 4. In the core type reactors the coils appear to surround the core.

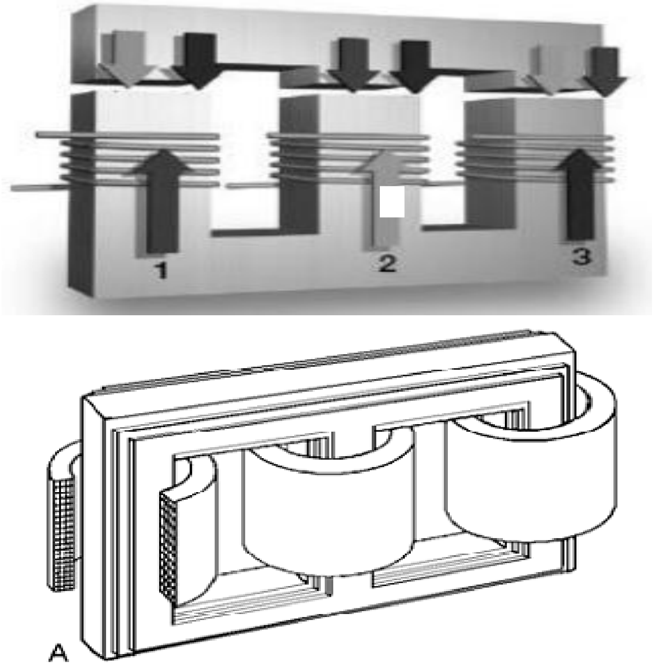

Figure 4. Three-leg shunt reactor core.

In a core type reactor the core limb has a shape of a cylinder around which the coils are arranged. For normal core type power reactors the coils too are cylindrical and arranged concentrically. Each terminal is connected to one coil or several coils in series. Further the coils are slid down around a pre-made core limb to which yokes are connected after the windings are in position. Most often the core limbs and yokes are in vertical position. The high-voltage reactor application usually calls for oil-immersed reactors that look very similar in appearance to power transformers. When designed an air-gapped iron core, these reactors can be equipped with a secondary core and winding such that a low-voltage can be extracted from the high-voltage line. A shunt reactor differs from a transformer in the facts the shunt reactor uses one winding per phase and that magnetic circuit has a gap. The gapped core type (Figure 5) is provided with a many number of gaps in tire legs arranged in the winding.

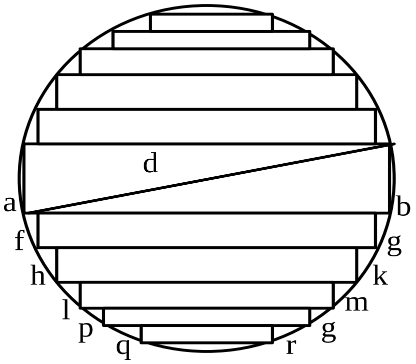

Figure5. Parallel laminated core type shunt reactor(11 step-core form).

A. Main Dimensions of Magnetic Frame

e.m.f equation, $E_1 = 4.44\ f\ B_m\ A_i$ **(1)**

e.m.f per turn, $E_t = K\sqrt{\dfrac{kVA}{phase}}$ **(2)**

Cross section area of the core, $A_i = k_i d^2$ **(3)**

Output of shunt reactor for three-phase,

$Q = 3.33 f B_m \delta K_w A_w A_i$ VA **(4)**

Window area, $A_w = L\ (D - d)$ **(5)**

Window space factor, $k_w = \dfrac{10}{30 + kV_1}$ **(6)**

Window area, $A_w = \dfrac{Q}{3.33 \times f \times B_m \times \delta \times k_w \times A_i}$ **(7)**

Width of window,

$b_w = D - d$ (for various stepped core) **(8)**

Center to center distance between the cores,

$D = b_w + d$ **(9)**

Overall length of the yoke, $W = 2D + 0.9d$ **(10)**

Gross core section, Ac=Ai/iron factor **(11)**

Gross yoke section, $A_y = 1.15A_c$ **(12)**

Width of the yoke, $b_y = 0.9d$ **(13)**

Height of the yoke, $h_y = \dfrac{A_y}{b_y}$ **(14)**

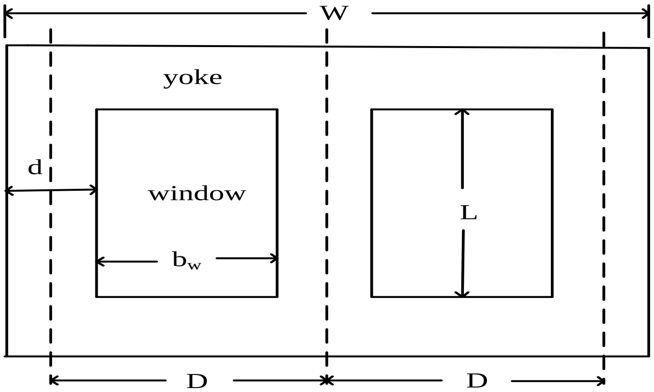

Figure 6. Main Dimensions of Magnetic Frame.

B. Performance Calculation of Magnetic Frame

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. The iron losses in the cores and yokes are mainly depended on the flux density used magnetic material (Figure 6).

Volume of the cores, $V_C = 3 \times A_c \times L$ **(15)**

Weight of the cores $= V_C \times$ Density of transformer steel **(16)**

Flux density in the core = 1.5 Tesla

Iron losses in the cores = B × Weight of core **(17)**

Volume of the yokes = $2A_yW$ **(18)**

Weight of yokes = Volume of yokes × Density of steel **(19)**

Iron losses in yokes = B × Weight of yokes **(20)**

C. No-load current

Length of flux path in the core, $AT_c = at_c \times L_c$ **(21)**

Total ampere turns for 3 cores = $3 \times AT_c$ **(22)**

Length of the flux path in the yokes, $AT_y = at_y \times L_y$ **(23)**

Total ampere turns for 2 yokes = $2 \times AT_y$ **(24)**

Total ampere turns for cores and yokes, $AT = AT_c + AT_y$ **(25)**

Total ampere turns per phase = AT/3 **(26)**

Number of turns per phase in winding, $T = V/E_t$ **(27)**

The r.m.s value of magnetizing current per phase,

$$I_m = \frac{\text{Total Ampereturns per phase}}{\sqrt{2} \times \text{Number of turns in h.v winding}} \quad \textbf{(28)}$$

r.m.s value of active component of no-load current per phase,

$$I_o = \sqrt{I_m{}^2 + I_w{}^2} \quad \textbf{(29)}$$

$$\text{Percentage no-load current} = \frac{\text{No-load current}}{\text{Rated current}} \times 100 \qquad \textbf{(30)}$$

No-load current of small shunt reactor may be of the order of 3 to 5 percent of the rated current, whereas in medium shunt reactors, it varies from 1 to 3 percent. In case of large shunt reactors, no-load current may be from 0.5 to 2 % of rated current.

D. Design of Shunt Reactor Winding

To design, the facts must be firstly considered number of turn per phase, conducted current and choosing of current density of wounded conductor for the secondary winding. And then, it needs to select the size of conductor and insulation of the shunt reactor winding.

Number of turns per phase in winding,

$$\text{Normal tap, } T = \frac{V}{E_t} \qquad \textbf{(31)}$$

$$\text{Current per phase, } \quad I = \frac{\sqrt{3}\times Q}{3\times V} \qquad \textbf{(32)}$$

Cross sectional area, a = I/δ **(33)**

According to cross sectional area, current rating and no. of turns, rectangular copper conductors are used. Continuous disc type winding with rectangular conductor is used for shunt reactor winding. The complete winding of each phase is sectionalized into discs. End coils have comparatively less number of turns, because of additional insulation. Number of turns of each disc will be arranged, axially and radially.

E. Efficiency of Shunt Reactor

Total losses at full load = Total iron losses + Total copper losses

$$\eta\ \%\ \text{of shunt reactor} = \frac{\text{Output Power}}{\text{Output Power} + \text{total losses}} \qquad \textbf{(34)}$$

F. Regulation

Per unit reactance, ε_x, for core type transformer with continuous disc winding is given by,

$$\varepsilon_x = \frac{2\,f\,\mu_0 l_{mt}(AT)}{L_c E_t}\left(a + \frac{b_1 + b_2}{3}\right) \qquad \textbf{(35)}$$

$$\varepsilon_r = \frac{\text{Total copper losses}}{\text{kVA rating}} \qquad \textbf{(36)}$$

Per unit regulation of the shunt reactor is given by,

$$\varepsilon = \frac{I_1(R_1\cos\theta + X_1\sin\theta)}{V_1} \times 100 \qquad \textbf{(37)}$$

G. Calculation of Shunt Reactor Tank

The assembled shunt reactor with magnetic frame and windings is housed in a proper tank, filled with oil, having good insulating properties. For shunt reactors of higher rating, tanks are constructed with external cooling tubes to provide additional surface heat dissipation. The cooling tubes could be circular or elliptical.

TABLE II: DETAIL DESIGN DATA SHEET OF 20 MVA SHUNT REACTOR

Specifications	Symbol	Unit	Design Values
Output	Q	VAR	25×10^6
Number of phase	-	-	3
Rated voltage	V_{Normal}	V	230000
Max. tap position voltage	$V_{Max.tap}$	V	245000
Frequency	f	Hz	50
Connection of winding	-	-	Star
Limit of temp: rise	θ	°C	50
Dimensions of Magnetic Frame			
Diameter of circumcircle	d	m	0.49
Length of core	L	m	1.86435
Length of yoke	W	m	2.2496
Height of yoke	h_y	m	0.4943
Width of yoke	b_y	m	0.441
Width of window	b_w	m	0.4143
Distance between core center	D	m	0.9043
Weight of cores	-	kg	8003
Weight of yokes	-	kg	7407
Winding Details			
Turn per phase	T	turns	1530
Phase current (max.)	I	A	69.73
Conductor section	a	mm^2	4.0×2.8
Inner diameter of winding	D_i	cm	61
Outer diameter of winding	D_o	cm	70.44
Radial width of winding	b	cm	12.24
Resistance per phase	r	Ω	2.811
Total reactance	X	Ω	98.265
Per unit resistance	ε_r	p.u	0.000831
Per unit reactance	ε_x	p.u	0.06717
Per unit resistance	ε_z	p.u	0.06717514
Per unit regulation at 0.8 p.f lagging	$\varepsilon_{0.8}$	p.u	0.0289
Per unit regulation at unity p.f	ε	p.u	0.00133
Performance Details			
No-load current	I_0	A	0.2858
Percentage no-load current	-	%	0.4554
Iron losses	P_i	kW	20.771
Copper losses	P_c	kW	43
Total full load losses	P_t	kW	64
Full load efficiency (unity p.f)	η	%	99.74
Full load efficiency (0.8 p.f)	$\eta_{0.8}$	%	99.68
Tank Details			
Length of tank	l_t	m	3.513
Width of tank	b_t	m	1.9044
Height of tank	h_t	m	4.353
Temp: rise without tubes	θ	°C	108.6
Number of cooling tubes	-	tubes	167

1. Calculation of Main Dimensions

To calculate main dimensions of tank, the following clearances have been assumed.

Total clearance length-wise, $\Delta l = 1$ m (assumed)
Total clearance width-wise, $\Delta b = 1.2$ m (assumed)

Total clearance height-wise, $\Delta h = 1.5$ m (assumed)

The length of the tank, $l_t = 2D + D_{o1} + \Delta l$

The width of the tank, $b_t = D_{o1} + \Delta b$

The height of the tank, $h_t = L + 2h_y + \Delta h$

2. Calculation of Temperature-rise

Cooling area of the tank wall, $S_t = 2\,(b_t + l_t)\,h_t$

Temperature rise, $$\theta = \frac{\text{Total losses}}{12.5 \times \text{tank area}} \qquad \textbf{(38)}$$

As the temperature rise is θ˚C high, cooling tubes must be provided to keep it with specified limit 50˚C (θ_1).

3. Number of Cooling Tubes

Heat dissipation by convection is inversely proportional to the viscosity and conductivity of oil. Heat dissipated is not affected by the color of heated surface. The effect of room temperature is also negligible on the heat dissipated by convection. For the design of shunt reactors, heat dissipated by convection can be taken as 6.5 watts per square meter of the tank surface per degree rise in temperature i.e. 6.5 for plain tank. Heat dissipated by convection is increased by the addition of tubes or radiators due to the siphoning effect. With addition of cooling tubes, the total losses to be dissipated in terms of temperature rise is given by,

$$\text{Total losses to be dissipated} = 12.5 S_t\theta_1 + (6.5 A_t\theta_1)1.35 \qquad \textbf{(39)}$$

Area of cooling tube = π × diameter of tube × length of tube.

VII. DISCUSSION AND CONCLUSION

A three-phase transformer which has three primary and three secondary voltage terminals, a three-phase shunt reactor has only three voltage connections. The shunt reactor is the most cost efficient equipment for maintaining voltage stability on the transmission lines. It does this by compensating for the capacitive charging of the high voltage AC-lines and cables. 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.

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IX. REFERENCES

[1] Hactor Ma-Ande Nojozi, 2012, “Evaluation of Replacing Fixed with Controllable Line Reactors in Mature Power System”, Dissertation for the Degree of Magister Ingeneriae (M. Ing) in (Electrical and Electronic) Engineering, University of Johannesburg.
[2] Cigre Working Group, August, 2012, “Protection, Monitoring and Control of Shunt Reactors”, Final Drafts, Cigre W. G. B5-37.
[3] M. Khorami, “Application Fields and Control Principles of Shunt Reactors with Tap-changer”, Master of Science Thesis, Division of Electric Power Engineering, Chalmers University of Technology, Göteborg, Sweden 2011.
[4] W.M. T. Mclyman., 2004. “Transformer and Inductor Design Handbook”, Third Edition, Revised and Expanded, Marcel Dekker, Inc. Idyllwild, California, U.S.A.
[5] James H. Harlow., 2004. Electric Power Transformer Engineering, CRC Press LLC.
[6] Nagrath I. J, “Power System Engineering”, Tata Mc-Graw Hill Publishing Company Limited, (2000).
[7] Dr. Mittle, V.N. and Arvind Mittal., 1996. “Design of Electrical Machine”, 5th Edition, Standard Publishers Distributors.
[8] T. J. E. Miller, (1982), “Reactive Power Control in Electric System”, Wiley & Sons Inc.