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Abstract: This paper compares the performance of thyristor controlled inductors (TCI), bank of capacitors and synchronous compensators in static VAR controls. Based on the analysis, thyristor controlled inductors offer a better and more efficient scheme so long as the firing angle of the thyristors are maintained above $\pi/2$. The flexibility in control as well as the switching speed of the thyristor is harnessed here. In conclusion, a practically implementable schematic arrangement of the optimal TCI is also shown.

Keywords: reactive power, real power, thyristors, inductors, capacitors and synchronous compensators.

1.0 Introduction

The loads that are supplied by electric utility systems consist of induction motors and induction furnaces which operate at a lagging power factor and hence account for most of the reactive power consumed in the system and domestic loads such as fans, lights and other appliances which operate at a power factor near unity. The power and distribution transformers act as reactive power loads because of the magnetizing current drawn by them. The loads in a three-phase network are usually unbalanced and give rise to negative sequence currents which also contribute to the reactive power consumed by the system. The overall effect is that the system operates at a low power factor. Such an operation has the following disadvantages:

With a highly lagging power factor, a large current flows through the system and causes considerable I^2R losses.

The kilovolt-ampere (KVA) loading on the system, which is given by $(KVA)^2 = (KW)^2 + (KVAR)^2$ increases because of high KVAR (reactive kilovolt-ampere) rating. Consequently, lower KW capacity of the generator will be available.

The voltage regulation at the load end, which is defined as leading to over voltages in the system and violation of the normally specified

regulation whose range is from -10% to +10%.

The above scenario is illustrated in figure 1. In the simple ac system, the line impedance is assumed to be equal to the line reactance neglecting the line resistance. It is seen from the phasor diagram that with I_p remaining constant, if I_q increases by ΔI_q the terminal voltage V_{td} decreases by ΔV_{td} .

This in turn results in a reduction of the real power P , in spite of I_p remaining constant [1, 2]. capacitor banks and synchronous compensators are today considered as unpopular schemes with numerous drawbacks that tend to defeat few gains either scheme may have.

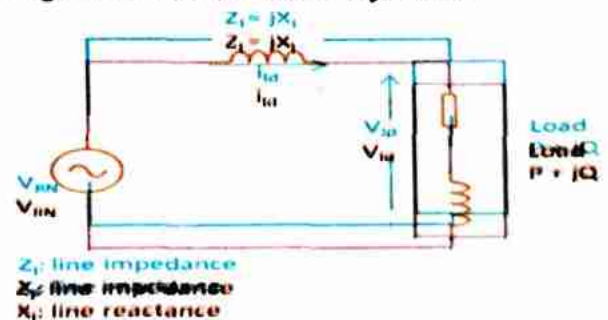


Figure 1a: A simple ac system.

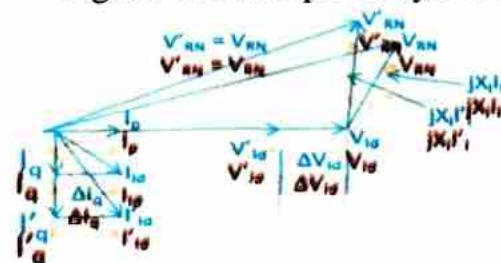


Figure 1b: A Phasor diagram of the simple ac system.

2.0 Literature Review

2.1 Capacitor Banks

The capacitor banks can provide the required amount of capacitance to the system, thereby supplying the required amount of KVAR to the system. But these banks suffer from the following demerits of the method of connecting the capacitor bank to the system also matters. There is the shunt capacitor configuration and there is also the series capacitor configuration. Among these two categories, shunt capacitors are more commonly used in the power system of all voltage levels. Agreed, there are few specific advantages of the shunt capacitor bank such as being capable of reducing line current of the system and improving the power factor of the source current, the principal element in both configurations remains a capacitor. Series capacitor particularly does not have any control over the flow of current. This is simply because it is connected in series with the load and the load current always passes through it. The major drawback here comes from the material with which capacitors are made, being very bulky; the bulk increases with further augmentation consequent to the increase in the substation load [6].

In the early stages of development, it was generally mineral insulating oil that was being used as impregnant. This has now been replaced by most of the manufacturers with synthetic liquids of chlorinated diphenyl group bearing different trade names. Though mineral insulating oil has very low electric conductivity and high dielectric strength, the following major problems remain a major disadvantage. The major drawbacks are:

- (a) The mineral insulating oil has low dielectric constant,
- (b) The voltage distribution in the mineral oil is never uniform,
- (c) It is very inflammable,
- (d) It is subject to oxidation.

There is also the problem of harmonics which causes capacitor overheating and failure.

2.2 Synchronous Compensators

Synchronous motors supply reactive power to the system when operated at a leading power factor. Such configurations are called synchronous condensers. However, the synchronous condenser is a very costly machine and installing one of such machine at every load center is not a feasible solution.

A synchronous condenser is a DC-excited synchronous motor, whose shaft is not connected to anything but spins freely [5]. Its purpose is not to convert electric power to mechanical power or vice versa, but to adjust conditions on the electric power transmission grid. Its field is controlled by a voltage regulator to either generate or absorb reactive power as needed to adjust the grid's voltage, or to improve the power factor. The synchronous condenser's installation and operation are identical to large electric motors and generators.

Increasing the device's field excitation results in its furnishing reactive power (VAR) to the system. Its principal advantage is the ease with which the amount of correction can be adjusted. The kinetic energy stored in the rotor of the machine can help stabilize a power system during rapid fluctuations of loads such as those created by short circuits or electric furnaces. Large installations of synchronous condensers are sometimes used in association with high-voltage direct current converter stations to supply reactive power to the alternating current grid. Unlike a capacitor bank, the amount of reactive power from a synchronous condenser can be continuously adjusted. Reactive power from a capacitor bank decreases when grid voltage decreases, while a synchronous condenser can increase reactive current as voltage decreases. However, synchronous machines have higher energy losses than static capacitor banks [5].

Most synchronous condensers connected to electrical grids are rated between 20MVAR (Megavars) and 200MVAR and are hydrogen cooled. What makes this scheme unpopular, uncommon and infeasible in most cases are the high cost of installing one, the danger of

hydrogen fire explosion together with the high precision requirement of determining hydrogen concentration.

2.3 Thyristor Controlled Inductors

A thyristor controlled inductor (TCI) can be treated as a variable inductor whose reactive power consumption can be controlled by changing the firing angle of the thyristors. This can be explained with the help of the two-terminal power system shown below. The generating station A supplies real power P_{ld} through the transmission line to meet the load power at station B as well as I^2R losses. The reactive power Q_{ld} required by the load has also to be transmitted through the same line, thus making the total power equal to $P_{ld} + jQ_{ld}$. Under full load conditions, the load power factor will be low, because the reactive power consumed as well as the load current will be quite high. It should be noted here that the load voltage decreases with an increase in current. The load voltage at the receiving end can also be restored by taking measures such as the provision of capacitor banks for power factor correction. This can be avoided by adopting the optimal thyristor controlled inductor scheme.

On the other hand, under light load conditions, the transmission line capacitance comes into the picture (called the *Ferranti effect*) and acts as a source of reactive power.

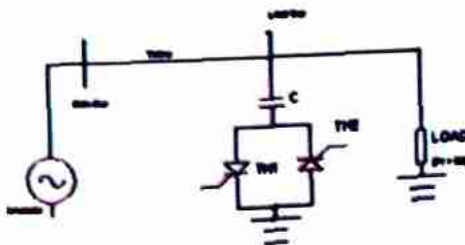


Figure 2: A typical two-terminal power system with a Thyristor Switched Capacitor at the load end.

Because of inadequate load inductance for the consumption of this reactive power, the load voltage magnitude may even exceed that of the sending end voltage. The load power factor will also be low, but this time it will be a leading one because of the flow of capacitive reactive power. Thyristor controlled inductors can

absorb this reactive power through the transmission line and restore normal conditions for the voltage as well as the power factor. The lower the load power under light load conditions, the greater will be the capacitive reactive power flow and the larger will be the magnitude of inductance required from the thyristor controlled inductor. The argument here, therefore, is that an optimal thyristor controlled inductor (TCI) scheme exists that is flexible enough, based on the thyristor firing angle manipulation, to control both power factor and load voltage variations.

Figure 3(a) below shows the circuit of a thyristor controlled inductor and figure 3(b) shows its equivalent. In the later the inductor is shown as a load fed from a single-phase ac controller. The analysis of such circuit is [6]:

$$L \frac{di}{dt} + Ri = V_m \sin \omega t \quad (1)$$

$$\text{for } \alpha < \omega t < \alpha_e \text{ and } \pi + \alpha < \omega t < \pi + \alpha_e$$

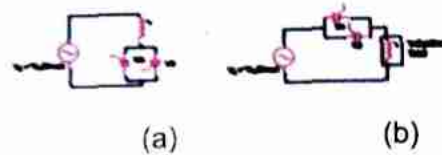


Figure 3a: An ac system with a TCI, figure 3b: the equivalent circuit.

The solution of equation (1) is of the form:

$$i(t) = \frac{V_m}{\omega L} \sin(\omega t - \phi) + A \exp\left(-\frac{R}{L}t\right) \quad (2)$$

where ϕ is the power factor angle, α is the firing angle of Th1 (conduction begins), α_e is the extinction angle of Th1 (conduction After substituting the initial condition ($i = 0$ at $\omega t = \alpha$) and final condition ($i = 0$ at $\omega t = \alpha_e$) and sorting out the terms containing α_e to one side, the complete solution of equation (2) becomes [6]:

$$e^{(\frac{R}{\omega L})\alpha} \sin(\alpha_e - \phi) = e^{(\frac{R}{\omega L})\alpha} \sin(\alpha - \phi) \quad (3)$$

With $\alpha > \phi$ the sinusoidal term on the left-hand side obeys the inequality $\sin(\alpha_e - \phi) > 0$ and this gives two values of α_e $\alpha_e - \phi < \pi$ or $\alpha_e > \phi$
The former inequality together with $\alpha_e - \alpha < \pi$
(4)

The (4) implies that the conduction is discontinuous and also shows that load voltage and current control is possible only under the condition that $\alpha > \phi$.

Equation (1) can be modified as

$$I_r \frac{di_{ld}}{dt} = V_m \sin \omega t \quad (5)$$

with the current i_{ld} starting with a zero value at a firing angle α and again becoming zero at α_e . Thus $i_{ld} = 0$ at $\omega t = \alpha$ and also at $\omega t = \alpha_e$ the latter serving as the final condition.

The ranges for current conduction in the positive and negative half-cycles are, respectively, $\alpha < \omega t < \alpha_e$ and $\pi + \alpha < \omega t < \pi + \alpha_e$. The solution of equation (3), with the initial condition $i_{ld} = 0$ at $\omega t = \alpha$ and the final value ωt is obtained as

$$\int di_{ld} = \frac{V_m}{\omega L} \int_{\alpha}^{\omega t} \sin \omega t dt \quad (6)$$

Evaluation of the integral and substitution of the initial and final values gives

$$i_{ld} = \frac{I_m}{\omega L} [\cos \alpha - \cos \omega t]$$

Also, the final condition on i_{ld} gives

$$\cos \alpha = \cos \alpha_e \quad (7)$$

This gives

$$\alpha_e = 2\pi - \alpha \quad (8)$$

From the arguments above, it is evident that for the circuit to work as an ac controller α must be greater

than $\pi/2$ radians since the current is always discontinuous with this condition on α [7]

If a Fourier analysis is done for this discontinuous periodic waveform of i_L , the RMS magnitude $i_{L1(eq)}$ of the fundamental component i_{L1} can be worked out as [8,9]:

$$i_{L1(eq)} = \frac{I_m}{\pi \omega L} [2\pi - 2\alpha + \sin 2\alpha] \quad (9)$$

$\pi/2 < \alpha < \pi$ and V_s is the RMS magnitude of the ac supply voltage (equal to $V_m/\sqrt{2}$). All the other harmonics of i_{L1} are odd, that is 3, 5, 7, 9, etc. by connecting a three-phase TCI in delta, the triple harmonics 3, 9, etc. circulate in the delta connectors and do not enter the system. Other harmonics such as 5, 7, etc., can also be eliminated by connecting series LCR filters across the system.

Figure 4 shows the optimal thyristor controlled inductor (OTCI) on a single-phase system. The capacitor, which is connected in parallel with the TCI, draws a fixed amount of current from the system and the net current can be varied by phase control of the thyristors. As the TCI and the capacitor C are connected in parallel, the total fundamental component of the reactive current drawn becomes,

$$I_R = I_c + I_{L1(eq)} \quad (10)$$

Writing I_R and $I_{L1(eq)}$ as given in (9) gives I_R as:

$$(11)$$

where I_c is taken to be equal to $V_s \omega C$ and with α in the range $\pi/2 \leq \alpha \leq \pi$, I_R will be capacitive or inductive in nature, depending on whether the first term in the square brackets on the right-hand side of (11) dominates the second one or vice versa. The two extreme values of I_R obtained with $\alpha = \pi/2$ and $\alpha = \pi$, therefore work out respectively to $V_s(\omega C - 1/\omega L)$ and $V_s \omega C$



Figure 4: Optimal TCI scheme with a fixed capacitor in parallel with a variable inductor.

3.0 Conclusion

The switching speed and flexible controls of the thyristor devices as well as their near zero maintenance are some of the major advantages that have been harnessed in this optimal configuration. Figure (4) is a practical implementable scheme of the optimal arrangement.

The thyristorized VAR controllers also called static VAR controllers [], the capacitor banks and synchronous condensers:

They form a power electronic interface between the system and the load, and provide quick control over the reactive power,

They are much cheaper and more compact than the conventional equipment, They prevent voltage flickers as well as rapid changes in the

reactive power caused by industrial loads, Such loads also present an unbalanced load condition for the three-phase system, and static VAR controllers can compensate for such imbalances, Static VAR controllers can also provide dynamic voltage regulation.

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