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Effect of Reactive Power Compensation and Power Factor Correction on Power System Performance

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ABSTRACT

This paper reviews the implementation of reactive power compensators and the power factor correction techniques in local network .Full description of the main aspects of reactive power compensation and power factor correction PFC is explained .First, factors related to reactive power compensation and power flow is presented .Then, power factor correction types and methods of implementation is presented. Finally, demonstrating the application of reactive power compensation and power factor correction on the local network on the different voltage levels with a conclusion .

Keywords - reactive power compensation ,power factor correction PFC.

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I. INTRODUCTION

During the last decades the demand on electrical power has been sharply increased .But the cost of producing electrical power also increased due to the increase of fuel. Therefore, resulting in a must to optimize the design and use of electrical power in all stages of generation , transmission , and distribution .Reactive power compensation and Power factor correction (PFC) are among these tools used to achieve the power optimization goal .Most of electrical systems ,equipment and devices consume two types of electrical power , active power and reactive power . Active power P measured in kw which is consumed and transformed to another type of energy like heat , mechanical , light and other types of energies depending on the load nature . The other one is the Reactive power Q measured in kvar which is not consumed and not transformed to another type of energy but used to build up and sustain the magnetic field in the load which is required by this type of loads to do its work. The addition of these two powers result in the third power namely the total apparent power S measured in kva . The power triangle Fig. 1.shows the relationship between P , Q , and S and their related currents IR ,IQ and I .

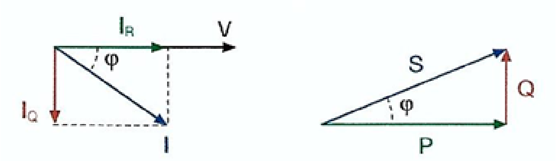

Figure 1. power triangle.

The angle between P and S is called the power angleφ and the cosine of the power angle is called the power factor PF which equals in an ideal case , ignoring the harmonics effect ,the ratio of active power P to the total apparent power S .

$$\mathrm{PF} = \cos\varphi = \frac{P}{S} \quad (1)$$

When reactive power Q is small will result in a small power angle and a large power factor PF becomesvery close to unity which means the useful active power is maximized which is our goal here. But as Q increased will result in a larger power angleφ and a smaller power factor PF which means we will consume useful active power P as a small portion of the total available apparent power S which supplies the load .Therefor, the power factor is a measure of the efficiency of the power system utilizing the available total power generated .

Loads are resistive , capacitive or inductive . For resistive loads current and voltage are in phase φ=0 and PF is unity .But for capacitive and inductive loads current and voltage are phase shifted by 90° resulting in a very low power factor PF =0 .Due to the 90° phase shift the average active power P=0 where power in capacitors is positive during the first quarter of the cycle and negative for the other quarter and so on for the remainder of the cycle Fig. 2.While for inductors is the opposite since active power P will be negative during the first quarter of the cycle and positive for the other quarter and so on for the remainder of the cycle Fig. 3.This means that capacitors and inductors are storing the electric energy delivered by the source during the first quarter of the cycle and returning back the energy to the source during the next quarter and so on .It seems to be that reactive power Q is useless since it travels between the load and the source for reactive loads but it is very essential for the work of many equipment and devices .

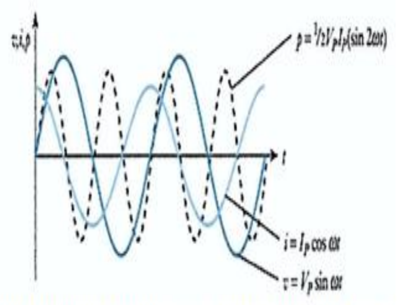

Figure 2.instantaneous reactive power in a capacitive load .

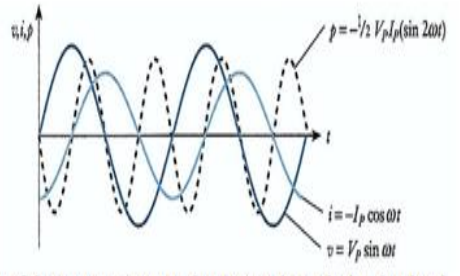

Figure 3.instantaneous reactive power in an inductive load .

Reactive power is required by many parts of the power system and loads to provide current to establish the magnetic field.The compensation of bulk power at the generation ,transmission , and distribution levels differ from those techniques and goals at the load level.At load level compensation , the main goals are power factor correction ,load balancing , and improvement of voltage regulation . Reactive power is absorbed in different systems ,equipment and devices in the network among thoseunder excited synchronous generators ,over-head transmission lines , under-ground cables over loaded with more than the surge impedance load SIL ,power transformers ,inductors ,motors ,arc furnaces ,welding machines and high intensity discharge lighting HID.Table 1. shows low PFtypically results from unloaded or lightly loaded motors where for unloaded motors the power factor might reach the low value of PF = 0.2.

Table 1. typical power factor for industrial loads.

Industry	Percent Uncorrected PF
Brewery	76-80
Cement	80-85
Chemical	65-75
Coal Mine	65-80
Clothing	35-60
Electroplating	65-70
Foundry	75-80
Forge	70-80
Hospital	75-80
Machine manufacturing	60-65
Metal working	65-70
Office building	80-90
Oil-field pumping	40-60
Paint manufacturing	55-65
Plastic	75-80
Stamping	60-70
Steelworks	65-80
Textile	65-75

While reactive power can be generated through , over excited synchronous generators ,over-head transmission lines , under-ground cables lightly loaded with less than the surge impedance load SIL ,capacitors ,synchronous motors ,static var compensators SVC ,static synchronous compensator STATCOM ,static synchronous series compensator SSSC , and unified power flow controller UPFC .

II. REACTIVE POWER COMPENSATION

Surge Impedance Loading is a very important issue in bulk reactive power compensation [1]. The surge Impedance Z_0 is a constant for a transmission line and is given by

$$Z_0 = \sqrt{\frac{l}{c}} \quad (2)$$

Wherel is the self inductance of the line and c is the self capacitance of the line.The surge impedance value depends on the over-head transmission line design . For high voltage over-head lines , the positive-sequence value typically lies in the range 200-400 Ω . When a transmission line is loaded by its surge impedance Z_0 then both V and I have a constant amplitude along the line Fig. 4. Then , the line is said to have a flat voltage profile

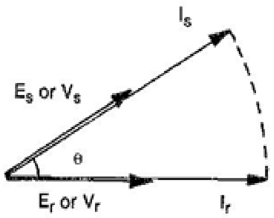

Figure4. phasor diagram of naturally loaded line

A line in this case is naturally loaded and the natural surge impedance load SIL is

$$P_0 = \frac{V_0^2}{Z_0} (3)$$

The surge impedance $Z_0$is a real number .Therefore, at the natural load the power factor is unity at all points along the transmission line , including the ends. This means that at the natural load no reactive power has to be absorbed or generated at either end of the line . The reactive power generated in the shunt capacitance of the line is exactly absorbed by the series inductance .Therefor, the natural load of the lineP_0 is the only value of transmitted power that gives a flat voltage profile and unity power factor at both terminals of the transmission line .So, if $P_0$is considered the natural power of the line , then the natural reactive power of the line is zero.

The excitation system of synchronous generators is a limited way of controlling the reactive power. The line charging reactive power for an open transmission line connected to a synchronous generator is given by

$$Q_S = -P_0 \tan\varphi \,(4)$$

The charging current leads the line terminal voltage by 90° and flows in the generator .This charging current could reach more than 0.4 p.u.of the generator rated current.Therefore , the reactive power absorption capability of synchronous generators is limited and can increase the heating of the ends of the stator coreand can also alters system stability. Therefore, other compensation tools should be used to absorb this reactive power Q_s .Shunt reactors, synchronous condensers, or static compensators can be connected at the receiving end or at points along the transmission line .

On-load tap changers are used in all power transformers in transmission main substations .It is used automatically to sustain the voltage levels within the determined ranges and in the same time changes xl the reactance of the power transformer and effects the reactive power of the grid in case of overloading and under loading .In the absence of compensating equipment , the reactive power required or generated by the line must be absorbed or generated by synchronous generators . Recently , static var compensators SVC using thyristor-controlled reactors TCR ,and thyristor-switched capacitors are developed and implemented to provide or absorb the needed reactive power [2]-[4].Pulse width modulation PWM and flexible ac transmission systems FACTS represents a new concept of operating and controlling electrical power systems [5] , [6]. Bulk reactive power compensation can avoid disastrous blackouts [7] ,[8] .

III. POWER FACTOR CORRECTION

The value of the power factor is a very important indicator for the quality of any electrical power system .The power factor is the ratio of active power P to the apparent power S which can present in intervals of 0 and 1 , and within real power networks is equal to 0.8 to 0.98 [9].Another indicator beside the power factor namely tan φ produced also from the powers triangle can be used .It represents the ratio of reactive power Q to the active power P where in some countries there is a certain Q allowable free percentage of P .

$$\tan\varphi = \frac{Q}{P} (5)$$

The main idea of the power factor correction is to provide the reactive power required by the load locally by connecting in parallel with the load a capacitor having a purely reactive admittance .The load current I_L consists of two components ,a resistive component I_R in phase with the source voltage V , and a reactive component $I_X$perpendicular with V as shown in Fig. 5.

$$I_L = I_R + jI_X (6)$$

Then, the apparent power supplied by the source to the load.

$$S_L = P_L + jQ_L (7)$$

Now, if a capacitor bank is added in parallel suppling a reactive powerQ_γ=-Q_L and a current
jI_γ=- jI_Xthen the source current I_S supplied by the source to satisfy the required load will be

$$I_S = I_L + I_\gamma = I_R (8)$$

Which in phase with the source voltage , resulting in an overall unity power factor as shown in Fig. 5.

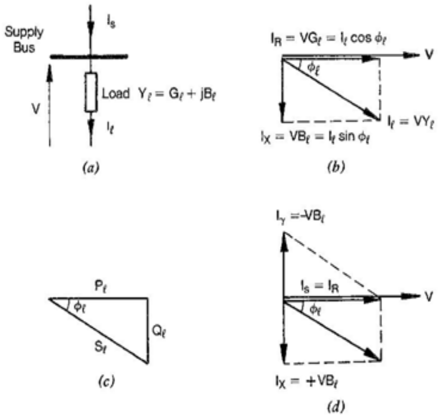

Figure 5.power factor correction

An ideal purely reactive compensator can eliminate source voltage variations caused by changes in the load .But it cannot maintain in the same time both constant voltage and instantaneous unity power factor.

Harmonics occurs due to non-linear loads. PFC equipment and its control circuits also participate in generating some harmonics. Power systems all over the world uses the fundamental frequencies of 50 HZ and 60 HZ .Any other frequencies rather than the fundamental called harmonics . Harmonics will result in distortion to ac sinusoidal current and voltage waves as shown in Fig. 6. [10].

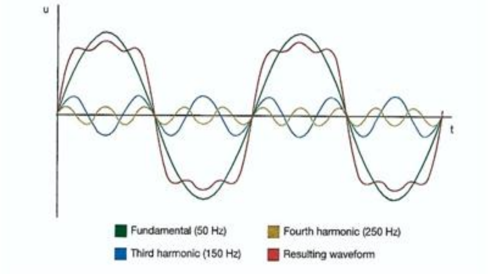

Figure6. distortion current and voltage waves due to harmonics

These harmonics are generated through non-linear loads like arcing devices , energization of power transformers ,power supplies UPS, thyristor-controlled reactor TCR ,reactive power compensators ,rectifiers and drives .These harmonics have a typical series of multipliers of the fundamental frequency and according to the non-linear load type. The effect of extra harmonics distortion will result in break-down of equipment and devices or at least will shorten the life of these equipment . It will lead to malfunction of protective relays since it will result in a modified zero crossing of the current ,alter the power factor and of course waste of electrical energy.The Total Harmonic Distortion THD measure provides the total distortion due to all harmonics in current and voltage waves [11].

$$\mathrm{THD-V}(\%) = \frac{\sqrt{\sum_{n=2}^{n} V_n^2}}{V_1} \times 100 \qquad (9)$$

Where
V_1=The rms voltage of the fundamental
V_n=The rms voltage of harmonic n

$$\mathrm{THD-I}(\%) = \frac{\sqrt{\sum_{n=2}^{n} I_n^2}}{I_1} \times 100 \qquad (10)$$

Where
I_1=The rms current of the fundamental
I_n=The rms current of harmonic order n

PF correction provides many benefits among them reduced electric utility bill ,increased system capacity (generators, cables, transformers) ,reduced losses in transformers and cables,improved voltage regulation ,greening the power system by reducing environmental impact through using less fuel.Power factor correction devices and equipmentcan be connected to the loads in many methods .Fixed capacitors, single or in groups Fig. 7 and Fig. 8, are used for motors working continuously and at no-load power transformers Fig. 7.

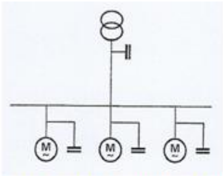

Figure 7. fixed capacitors for power factor correction.

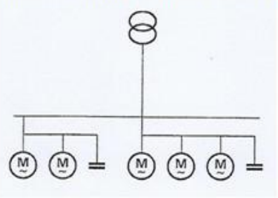

Figure 8.grouped fixed capacitors for power factor correction.

Automatic capacitors are more commonly used and controlled automatically through automatic reactive power control relays and are connected to the main distribution board Fig. 9 or another alternative by using a combination of all methods using the hybrid method of connection Fig. 10.

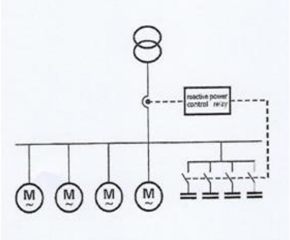

Figure 9.automatic connection of power factor correction capacitors

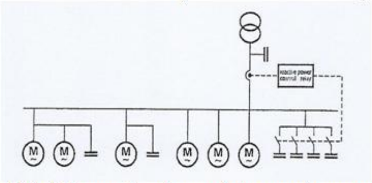

Figure 10.hybrid connection of power factor correction capacitors.

The detuned reactors (DR) are designed to protect the capacitors by preventing amplification of the harmonics present on the network. They must be connected in series with the capacitors Fig. 11.

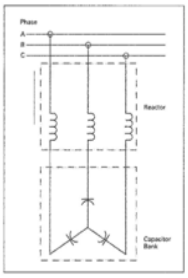

Figure 11.detuned reactors in series with capacitor banks.

IV. IMPLEMENATION OF BULK REACTIVE POWER COMPENSATION AND POWER FACTOR CORRECTION IN LOCAL GRID

Bulk reactive power compensation is mainly used to maintain the reactive power absorbed or generated by the power system main components like over-head transmission lines OHTL , under-ground cables UGC and power transformers through other sources rather than the synchronous generators in power plants. It also participates in controlling the power flow through the grid via controlling both the voltage magnitudes and phase angles at different sending and receiving main substations . The National Control Centre NCC and four District Control Centers DCC supervise and control the bulk reactive power compensation. The weather locally in summer is considered to be one of the hottest in the region around. The power network is heavily loaded during most of the year through air conditioning and air cooling systems inductive loads. Therefore, the network requires a lot of reactive power to be absorbed by such loads. The required reactive power is supplied through under-ground cables UGC .The reactive power is injected to the grid at different voltage levelsto maintain an overall power factor close to 0.95 .Tie UGC are used for more security purposes to connect 400kv and 300kv substations together as a spare cable in case of faults or maintenance and so on for other voltage levels substations of 132kv, 33kv and 11kv . These UGC are shown opened from one end at all different voltage levels in Fig. 12.These cables are normally opened from both sides but in case needed for bulk reactive power compensation they will be energized by connecting them from one end of the tied substations .The reactive power Q injected by UGC to the grid depends on UGC voltage level and length .Then, the NCC engineer has a plenty of UGC at different voltage levels and ratings where he can utilize them to inject the required Q to the network to keep total power factor within the target range .

During winter the network load is very light since air conditioning loads not any more needed.Therefore ,the capacitive currents due to the network OHTL and UGC are dominant resulting in a poor leading PF and must be compensated locally by inductive currents .This compensation is carried out by connecting shunt reactors in different ratings and different points in the network as described hereafter and as shown in Fig. 12.

1) Connecting 250 MVAR shunt reactors at the middle point of 400kv and 300kv over-head transmission lines .
2) Main substations (300/132/33)kv are composed of 2 tertiary power transformers of 300MVA rating and the tertiary winding is 33kv and used as a shunt reactor of 45MVAR .Resulting in an ability to absorb 90MVAR.The network composed of more than 30 of such a substations yields a total availability of 2700MVAR to be absorbed from the grid.
3) Connecting 50 MVAR shunt reactors at the middle point of 132kv over-head transmission lines .
4) In main substations (132/11)kv a shunt reactor of 50MVAR is connected to the 132 kv bus bar.
5) In main substations (33/11)kv a shunt reactor of 50MVAR is connected to the 33 kv bus bar.

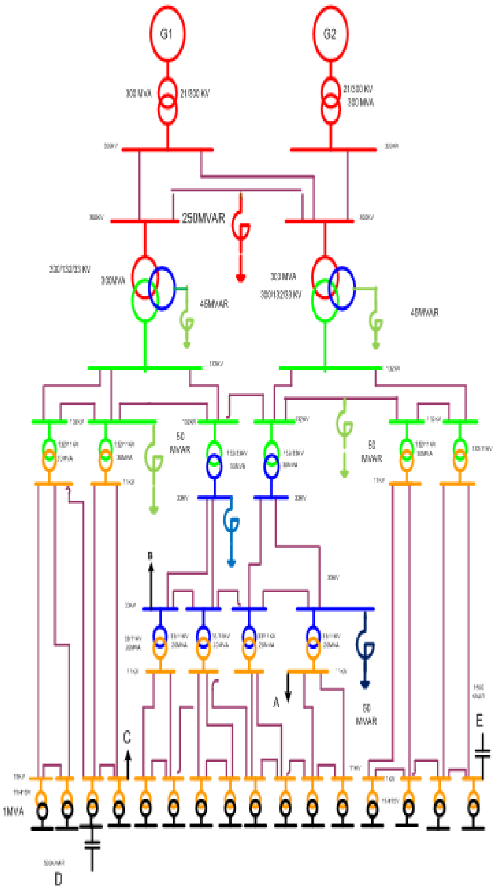

Figure 12.bulk reactive power compensation on local grid.

Therefore, reactive power is available at different voltage levels, critical nodes of the grid and different values. An NCC engineer will insert part of these shunt reactors according to the grids requirement to achieve the best performance in terms of total power factor, stability, load sharing and voltage profiles. The transmission system composed of overhead transmission lines and under-ground cables at voltage levels 400, 300, 132, 33 KV .The reactive power per each kilometer for overhead lines

1) 400 KV 6.5 MVAR/ Km .
2) 300Kv 2.5 MVAR/ Km .

Locally, power factor correction PFC can be classified into two sectors , industrial and residential.

1) Industrial loads are mainly inductive motors consuming reactive power with low power factor. These industrial factories are obliged to install PFC equipment and devices at their own premises to satisfy their reactive power requirement needs.Their bills covers both active and reactive power consumption and have measuringinstrument for that.MEW supplies heavy industrial by 33kv feeders and most other industrial by 11kv feeders as marked respectively B and A in Fig. 10.Then , they transform the voltages according to their own requirements .Inspection is carried out by MEW technicians and engineers to guarantee a complete commitment of these factories to the PFC policy and a penalty is given to those not applying fully or partially PFC.

2)Residential buildings and houses represents the major part of load to the grid .These loads normally have a low power factor within 0.75 lagging range where most of them are home appliancesrotating machines like washing machines, drying machines,dish washing machines,air conditioning ,refrigerators ,TV, personal computers and others. Its true they are not all running 24 hours but in terms of quantity they are very huge. These multi-store residential buildings , villas , offices and houses are not obliged by MEW to install PFC and their bills covers only the active power consumption .

Recently , MEW solved this problem partially by forcing the owners of multi-storebig new buildings to install PFC with certain specifications[12] .Among these specifications are the power factor correction capacitor banks shall be switched on/off automatically in steps through the use of Electromagnetic Contactors designed for capacitor switching or shall be thyristor controlled depending on the type of electrical loads and shall incorporate series reactors for harmonic current suppression and to prevent resonance.The ratings of the capacitor banks to be installed and connected at the LV board buses of the ring main distribution substations for transformer rating of 1000 KVA shall be as follows.

1) 500 KVAR, to be switched automatically in steps of 1:1:2:2:2:2 (i.e., 50/50/100/100/100/100KVAR)
2) 350 KVAR, to be switched automatically in steps of 1:2:2:2 (i.e., 50/100/100/100 KVAR) .

The total losses including discharge resistors to be less than 0.5 Watt/KVAR.The automatic power factor controller shall be microprocessor based VAR Sensing type .The controller shall be able to sense the reactive current requirement and switch on/off to the required stage of the capacitor bank. The automatic power factor controller shall maintain a targeted power factor within 0.95 lagging and unity.

But all old multi-store buildings and all houses and villas ,which represents a very huge load, are not obliged to install PFC. The installation of PFC equipment and devices can be carried out within MEW premises at the ring main distribution substations (11/0.415) kvfor the ease of supervision ,maintenance and control. Capacitor banks can be installed on the 11kv bus bar marked E and C on Fig. 12 or at 415v bus bar marked D on

Fig. 12 or at the consumer premises .Preferably at 415 v bus bar since in this case even the power transformers and all other upper stream power elements make use of the reduction of the reactive current. Installing capacitor banks of 1000KVAR ,500KVAR and 350KVAR in different ring main distribution substations and consumer premises shows the saving of 10%-20% in total apparent power. The number of the ring main distribution substations are now more than 6000 substation and they are increasing with the expansion of the grid. Therefore, the quantity of apparent power to be saved is very large and so is its effect on the power system total performance.

V. CONCLUSION

1) Bulk reactive power compensation tools namely synchronous generators excitation system ,on-load tap changers, shunt reactors and energized under-ground cables are adequate for reactive power compensation of the main parts of the grid and as the grid expands these tools also expand respectively.
2) PFC for the newly constructed multi-store buildings improves the local power factor and the overall system power factor.
3) PFC policy must be applied to the old multi-store buildings , houses and villas to contribute to the improvement of the grid performance.
4) Applicationof bulk reactive power compensation and PFC at all ring main distribution substations will improve substantially the power system total performance in terms of stability, increasingsystem capacity ,reducing losses, improving voltage regulation and reduces the energy production cost and the bill for the consumers .

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