Volume 6, Issue 2, April 2019 ISSN: 2348-8565 (Online)

International Journal of Modern Engineering and Research Technology

Website: http://www.ijmert.org Email: editor.ijmert@gmail.com

Analytical Study of Power Factor and Different Methods for Power Factor Correction

Hites V. Paghadar
Associate Professor
Electrical Engineering Department,
OM Engineering College,
Jungadh, Gujarat, India
Email: hvpaghadar@gmail.com

Chirag N. Jasani
Principal
Sanjaybhai Rajguru College of Diploma Engineering,
Rajkot, Gujarat, India
Email: chiragjasani@yahoo.com

Abstract

In the most common case, in the presence of ohmic inductive type loads, the total current I lags with respect to the active component IR. Therefore, in an electrical installation, it is necessary to generate and transmit, in addition to the active power P, a certain reactive power Q, which is essential for the conversion of the electrical energy but is not available to the load because exchanged with the network. This paper represents the different types of power factor correction methods and necessary calculation for power.

The complex of the power generated and transmitted constitutes the apparent power S. Power factor cosΦ is defined as the ratio between the active component IR and the total value of the current I; Φ is the phase angle between the voltage and the current. Improving the power factor means taking the necessary steps to increase the power factor in a defined section of the installation by locally delivering the necessary reactive power so that the value of the current and consequently of the power flowing through the upstream network can be reduced, at the same required output power.

Keywords:— *Power factor correction, reactive power calculassions, Power quality*

I. Introduction

Power factor correction is the term given to a technology that has been used since the turn of the20th century to restore the power factor to as close to unity as is economically viable. This is normally achieved by the addition of capacitors to the electrical network which compensate for the reactive power demand of the inductive load and thus reduce the burden on the supply. There should be no effect on the operation of the equipment. To reduce losses in the distribution system, and to reduce the electricity bill, power factor correction, usually in the form of capacitors, is added to neutralize as much of the magnetizing current as possible. Capacitors contained in most power factor correction equipment draw current that leads the voltage, thus producing a leading power factor. If capacitors are connected to a circuit that operates at a nominally lagging power factor, the extent that the circuit lags is reduced proportionately. Typically the corrected power factor will be 0.92 to 0.95. Some power distributors offer incentives for operating with a power factor of better than 0.9, for example, and some penalize consumers with a poor power factor. There are many ways that this is metered but the net result is that in order to reduce wasted energy in the distribution system, the consumer is encouraged to apply power factor correction. Most Network Operating companies now penalize for power factors below 0.95 or 0.9.

II. Different Methods for Power Factor Correction

It is important to understand where the capacitors are to be installed for a better exploitation of such advantages. There are no general rules applicable to every type of installation and, in theory, capacitors can be installed at any point.

According to the location modalities of the capacitors, the main methods of power factor correction are:

- Distributed power factor correction;
- Group power factor correction;
- Centralized power factor correction;
- Combined power factor correction;
- Automatic power factor correction

1. Distributed power factor correction

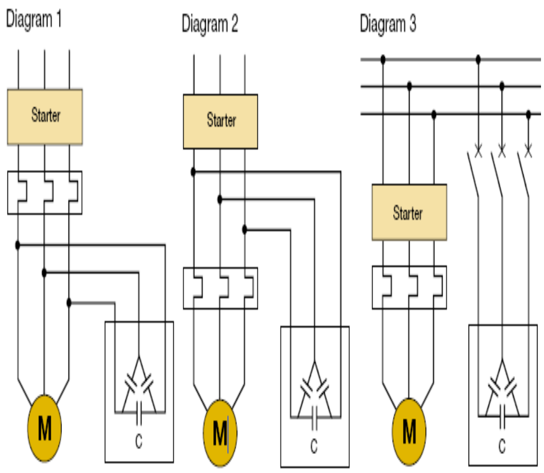

Figure 1. Common Connection Diagrams for the Power Factor Correction of Motors.

Distributed power factor correction is achieved by connecting a capacitor bank properly sized directly to the terminals of the load which demands reactive power. The installation is simple and inexpensive; capacitor and load can use the same protective devices against over currents and are connected and disconnected simultaneously. This type of power factor correction is advisable in the case of large electrical equipment with constant load and power and long connection times and it is generally used for motors and fluorescent lamps.

In case of direct connection (diagrams 1 and 2), the following risk may be run: after the disconnection from the supply, the motor will continue to rotate (residual kinetic energy) and self-excite with the reactive energy drawn from the capacitor bank, and may turn into an asynchronous generator. In this case, the voltage on the load side of the switching and control device is maintained, with the risk of dangerous over voltages (up to twice the rated voltage value). When using diagram 3, the compensation bank is connected only after the motor has been started and disconnected in advance with respect to the switching off of the motor supply. With this type of power factor correction the network on the supply side of the load works with a high power factor; on the other hand, this solution results economically onerous.

2. Group Power Factor Correction

It consists in improving locally the power factor of groups of loads having similar functioning characteristics by installing a dedicated capacitor bank. This is the method reaching a compromise between the inexpensive solution and the proper management of the installation since the benefits deriving from power factor correction shall be felt only by the line upstream the point where the capacitor bank is located.

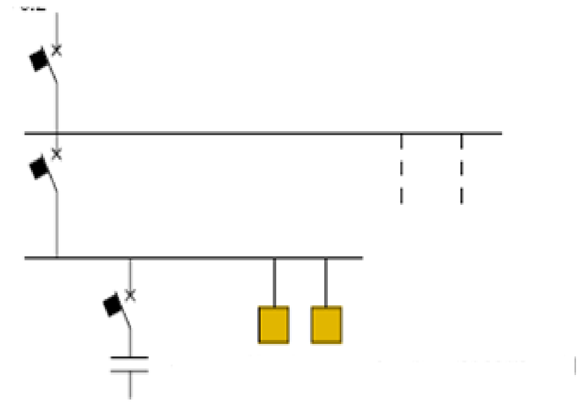

Figure 2. Groups of Loads to be Power Factor Corrected

3 . Centralized Power Factor Correction

The profile of loads connected during the day has a primary importance for the choice of the most convenient type of power factor correction. For installations with many loads, where not all the loads function simultaneously and/or some loads are connected for just a few hours a day, it is evident that the solution of distributed power factor correction becomes too onerous since many of the installed capacitors stay idle for a long time. Therefore the use of one compensation system only located at the origin of the installation allows a remarkable reduction of the total power of the installed capacitors. In centralized power factor correction automatic assemblies are normally used (see below automatic power factor correction) with banks divided into steps, installed directly in the main distribution boards; the use of a permanently connected bank is possible only if the absorption of reactive energy is quite constant all day long. The centralized solution allows an optimization of the costs of the capacitor bank, but presents the disadvantage that the distribution lines on the load side of the power factor correction device shall be sized keeping into account the full reactive power absorbed by the loads.

4. Combined Power Factor Correction

This solution derives from a compromise between the two solutions of distributed and centralized power factor correction and it exploits the advantages they offer. In such way, the distributed compensation is used for high power electrical equipment and the centralized modality for the remaining part. Combined power factor correction is prevailingly used in installations where large equipment only are frequently used; in such circumstances their power factor is corrected individually, whereas the power factor of small equipment is corrected by the centralized modality.

5. Automatic Power Factor Correction

In most installations there is not a constant absorption of reactive power for example due to working cycles for which machines with different electrical characteristics are used. In such installations there are systems for automatic power factor correction which, thanks to a monitoring varmetric device and a power factor regulator, allow the automatic switching of different capacitor banks, thus following the variations of the absorbed reactive power and keeping constant the power factor of the installation constant.

An automatic compensation system is formed by:

- some sensors detecting current and voltage signals;
- an intelligent unit which compares the measured power factor with the desired one and operates the connection and disconnection of the capacitor banks with the necessary reactive power (power factor regulator);
- an electric power board comprising switching and protection devices;

- some capacitor banks.

To supply a power as near as possible to the demanded one, the connection of the capacitors is implemented step by step with a control accuracy which will be the greater the more steps are foreseen and the smaller the difference is between them

III. Analytical Study of Power Factor

1. Calculations of the Power Factor

For the dimensioning of the capacitor bank to be installed in order to improve the power factor of a plant, it is necessary to calculate correctly the power factor according to the consumption or to the load cycle of the plant; this in order to avoid the intake of excess reactive energy, which is a condition normally forbidden by power supply authorities.

To carry out distributed or group power factor correction, it is necessary to calculate the cosϕ of the single load or of the group of loads (factory areas); this can be carried out as follows:

- directly, through direct measuring by means of a power factor meter;
- indirectly, through the reading of the active and reactive energy meters.

The power-factor meter is a measuring instrument able to display the power factor cosϕ according to which the load is absorbing energy. The reading of the instrument shall be carried out in different moments of the load cycle, so that an average power factor value can be obtained. If the readings of the active and reactive energy absorbed by the load or by the whole of the loads constituting the factory areas during a work cycle are available, the average power factor can be calculated as follows: where: EPi and EQi are the values of active and reactive energy read at the beginning of the work cycle; EPf and EQf are the values of active and reactive energy read at the end of the work cycle. To carry out a centralized power factor correction, the average monthly power factor can be obtained as previously illustrated or directly from the bills of the power supply authority.

2. Calculations of Necessary Reactive Power

Once the power factor (cosϕ1) of the installation and the power factor to be obtained (cosϕ2) are known, it is possible to calculate the reactive power of the capacitor bank necessary to improve the power factor.

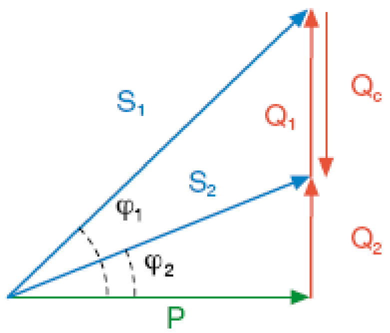

Figure 3. Reactive Power

Indicating by:

- P the installed active power
- ϕ1 the phase displacement angle before power factor correction
- ϕ2 the phase displacement angle to be obtained with the power factor correction

Once the initial cosϕ is known, Table 1 allows to calculate (in kvar per kW installed) the power of the capacitor bank necessary to obtain a defined power factor. In a three-phase system, the capacitor bank constituted by three capacitors having the same capacitance, can be delta- or star-connected. When selecting the connection modality, it is necessary to keep into account that with delta connection, each capacitance is subject to the supply line-to-line voltage, but, at the same level of generated reactive power, it has a value equal to 1/3 of the value it will have in case of star-connection:

$$Q_{cY} = Q_{c\square} \quad C_Y = 3 \cdot C_{\square}$$

In the low voltage field, where insulation problems are less important, the delta connection is usually preferred for the capacitor bank, since it allows a smaller sizing of the capacitances of each phase.

Table 1. Factor K (kvar/kW)

	final cosφ												
initial cosφ	0.80	0.85	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1
0.60	0.583	0.714	0.849	0.878	0.907	0.938	0.970	1.005	1.042	1.083	1.130	1.191	1.333
0.61	0.549	0.679	0.815	0.843	0.873	0.904	0.936	0.970	1.007	1.048	1.096	1.157	1.299
0.62	0.515	0.646	0.781	0.810	0.839	0.870	0.903	0.937	0.974	1.01 5	1.062	1.123	1.265
0.63	0.483	0.613	0.748	0.777	0.807	0.837	0.870	0.904	0.941	0.982	1.030	1.090	1.233
0.64	0.451	0.581	0.716	0.745	0.775	0.805	0.838	0.872	0.909	0.950	0.998	1.058	1.201
0.65	0.419	0.549	0.685	0.714	0.743	0.774	0.806	0.840	0.877	0.919	0.966	1.027	1.169
0.66	0.388	0.519	0.654	0.683	0.712	0.743	0.775	0.810	0.847	0.888	0.935	0.996	1.138
0.67	0.358	0.488	0.624	0.652	0.682	0.713	0.745	0.779	0.816	0.857	0.905	0.966	1.108
0.68	0.328	0.459	0.594	0.623	0.652	0.683	0.715	0.750	0.787	0.828	0.875	0.936	1.078
0.69	0.299	0.429	0.565	0.593	0.623	0.654	0.686	0.720	0.757	0.798	0.846	0.907	1.049
0.70	0.270	0.400	0.536	0.565	0.594	0.625	0.657	0.692	0.729	0.770	0.817	0.878	1.020
0.71	0.242	0.372	0.508	0.536	0.566	0.597	0.629	0.663	0.700	0.741	0.789	0.849	0.992
0.72	0.214	0.344	0.480	0.508	0.538	0.569	0.601	0.635	0.672	0.713	0.761	0.821	0.964
0.73	0.186	0.316	0.452	0.481	0.510	0.541	0.573	0.608	0.645	0.686	0.733	0.794	0.936
0.74	0.159	0.289	0.425	0.453	0.483	0.514	0.546	0.580	0.617	0.658	0.706	0.766	0.909
0.75	0.132	0.262	0.398	0.426	0.456	0.487	0.519	0.553	0.590	0.631	0.679	0.739	0.882
0.76	0.105	0.235	0.371	0.400	0.429	0.460	0.492	0.526	0.563	0.605	0.652	0.713	0.855
0.77	0.079	0.209	0.344	0.373	0.403	0.433	0.466	0.500	0.537	0.578	0.626	0.686	0.829
0.78	0.052	0.183	0.318	0.347	0.376	0.407	0.439	0.474	0.511	0.552	0.599	0.660	0.802
0.79	0.026	0.156	0.292	0.320	0.350	0.381	0.413	0.447	0.484	0.525	0.573	0.634	0.776
0.80		0.130	0.266	0.294	0.324	0.355	0.387	0.421	0.458	0.499	0.547	0.608	0.750
0.81		0.104	0.240	0.268	0.298	0.329	0.361	0.395	0.432	0.473	0.521	0.581	0.724
0.82		0.078	0.214	0.242	0.272	0.303	0.335	0.369	0.406	0.447	0.495	0.556	0.698
0.83		0.052	0.188	0.216	0.246	0.277	0.309	0.343	0.380	0.421	0.469	0.530	0.672
0.84		0.026	0.162	0.190	0.220	0.251	0.283	0.317	0.354	0.395	0.443	0.503	0.646
0.85			0.135	0.164	0.194	0.225	0.257	0.291	0.328	0.369	0.417	0.477	0.620
0.86			0.109	0.138	0.167	0.198	0.230	0.265	0.302	0.343	0.390	0.451	0.593
0.87			0.082	0.111	0.141	0.172	0.204	0.238	0.275	0.316	0.364	0.424	0.567
0.88			0.055	0.084	0.114	0.145	0.177	0.211	0.248	0.289	0.337	0.397	0.540

3. Harmonic Filters

Capacitor banks can be used combined with inductors in order to limit the effects of the harmonics on a network. Actually, the combination capacitor-inductor constitutes a filter for harmonics.

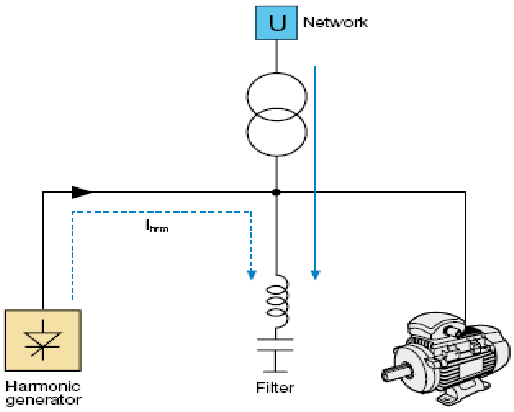

Figure 4. Harmonic Filter

Therefore this filter, called passive filter, consists in a capacitor connected in series with an inductor so that the resonance frequency is altogether equal to the frequency of the harmonic to be eliminated. Passive filters, which are defined on a case by case basis, according to a particular harmonic to be filtered, are cost-effective and easy to be connected and put into function.

Active filters instead can automatically eliminate the current harmonics present in a network in a wide range of frequencies. Exploiting power electronic technology, they can inject a system of harmonics able to neutralize those present in the network.

Previously it has been illustrated how, to avoid the negative effects of resonance, it is necessary to insert an inductor in series with a capacitor. By applying an analogous reasoning, it is possible to think of placing in a point of the network a combination of an inductor and a capacitor properly dimensioned in order to get the same resonance frequency of the order of the current harmonic to be eliminated. In this way, the assembly inductor-capacitor presents a very low reactance in correspondence with the harmonic to be eliminated which shall circulate in the assembly without affecting the whole network.

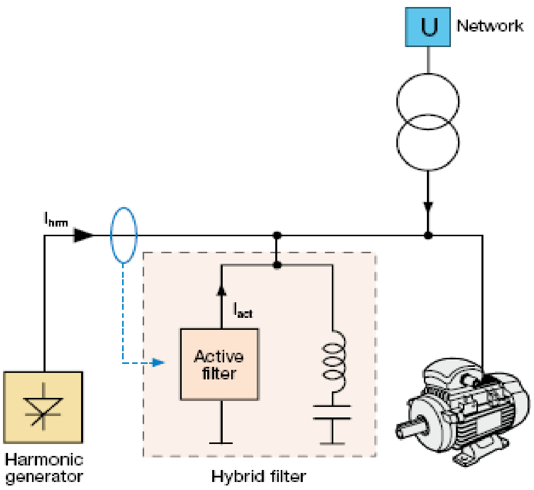

Figure 5. Hybrid Filter

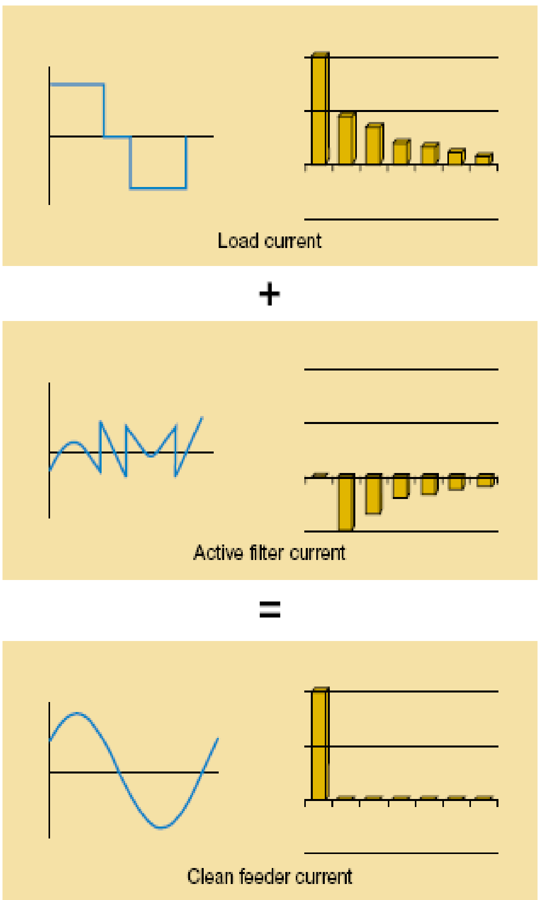

Figure 6. Harmonic Order

The active filter has the advantage of filtering simultaneously dozens of harmonics and does not involve design costs for dimensioning.

IV. CONCLUSION

This technical paper has the purpose of analyzing these problems without going into technical details, but, starting from the definition of power factor correction, from an analysis of the technical-economical advantages and describing the forms and modalities to achieve power factor 6 correction, it wishes to guide to the convenient choice of the devices for the switching of the capacitor banks and the filtering of the harmonics.

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