Optimization Techniques for Improved Power Factor and Energy Efficiency

K. Umamaheswari, Ramachandran M, Sathya.S, Preetha Sukumar

***Abstract:** Poor power quality like reduced power factor and elevated levels of harmonic distortion generate a number of problems for electrical utilities, and large industrial consumers are typically charged consequently. Condensed power factor is such a common problem based on typical loads that techniques are frequently applied to improve power factor when it is less than certain levels. Traditional procedures for increased power factor typically consist of adding power factor correction capacitors to deliver the reactive volt-ampere reactive (VARs) near the location that inductive loads are absorbing VARs. In adding up to inductive loads creating reduced lagging power factor, power electronic devices often reduce power factor similarly. Power electronic devices have become so commonly used that sophisticated techniques have been developed to improve power factor and reduce current total harmonic distortion for such devices. A common technique utilized for processes that must provide a large range of possible voltages is to include added transformer taps coupled with the power electronic devices. In addition to traditional methods for increasing power factor, by careful consideration during the design phase of processes and load cycles that have a repetitive nature, power factor can be improved. Such a method uses a computer algorithm approach to find the ideal compromise of the relevant design parameters for improved energy efficiency and power factor.*

***Keywords:** Power Factor, Energy Efficiency, THD, Industrial Process, Optimization Technique, VAR.*

I. INTRODUCTION

Electrical power transmission and distribution systems have a unique advantage of being able to convert energy from a primary energy source and transmit electrically over long distances to remote sites where it can be re-converted to mechanical energy (via electric motors), heat (via electric heaters) or other forms as desired by the end user; residential, commercial and industrial. It can be seen in Figure 1.1 that 40% of the total energy usage is for conversion to electric power [1], the majority which is lost during the thermodynamic conversion process. The remainder of the electrical energy is provided to the remote end users via high voltage transmission and distribution lines.

Revised Version Manuscript Received on November 08, 2018.

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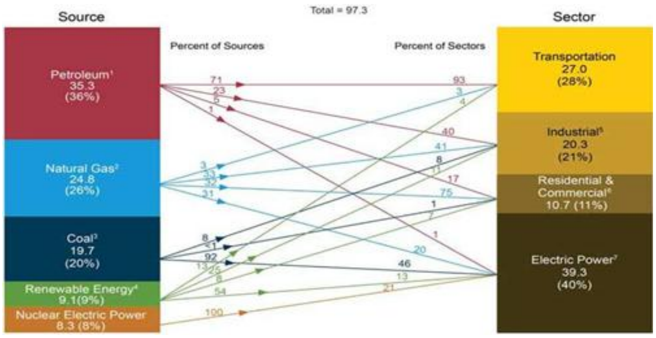

Figure 1: Total U.S. Energy in Quads of British Thermal Units

The end user utilizing the electrical energy must pay for the cost of the original fuel source and additionally must indirectly pay the capital costs of equipment, operational and maintenance costs to provide the energy, as well as losses incurred due to system inefficiencies. The general structure of the electrical generation, transmission and distribution system is shown in Figure 2.

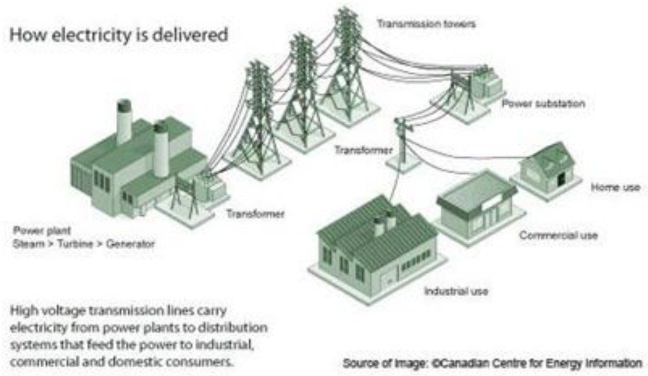

Figure 2: How Electrical Energy is Delivered

Generators are used to convert the original fuel source (coal, nuclear, hydro, etc.) to electrical power in the form of voltage and current. The product of the voltage and current is the electrical power being generated and is typically given in units of Watts. One Watt is one Joule of energy used each second (J/s). Since a Watt is such a small unit of power, kilo-watts (kW) or Mega-watts (MW) are more commonly used terms when describing electric power. To reduce transmission losses and reduce line currents to a level practical for electrical conductors used for transmission, transformers at a substation are used to raise the voltage and reduce the current from the originally generated power. Energy and power must be conserved so any increase in voltage must result in a corresponding decrease in current. Near the end user, transformers are once again used to reduce voltage to a level practical for the end user (industrial, commercial, residential) to utilize.

As the electrical power is transferred over long distances as well as each time transformations occur, some of the originally converted energy is lost from the system primarily in the form of heat but also mechanical vibration, sound, etc. Although the electrical utility is responsible for providing the power to the end user as efficiently as possible, once delivered, the end user pays for the energy they utilize including the energy lost due to inefficiencies from of how the end user utilizes the energy. For instance, an industrial plant using an electric heater will pay more on their energy bill for a less efficient heater than a heater that uses the energy more efficiently.

The most common situations where the current is not perfectly in phase with the voltage is for inductive and capacitive loads. In inductive loads, energy is stored in the magnetic field and then return to the source. In capacitive loads, the energy is stored in the electric field and then returned to the source. In the case of inductive loads, the current lags behind the voltage by 90 degrees and in the case of capacitive loads, the current leads the voltage by 90 degrees. Inductive and capacitive loads tend to counter balance one another and can be used to bring the current in phase with the applied voltage. When the current is intentionally corrected to be in phase with the voltage, it is called *power factor correction*. For inductive and capacitive electrical loads, it was mentioned that the power is supplied to the load and then power is supplied from the load back to the source.

This reactive interaction between the source and load is called *reactive power* and is defined by the quantity Q in equation 1.

$$Q = V_{RMS} I_{RMS} \sin(\phi) \qquad (1)$$

The real power P, reactive power Q and apparent power S are orthogonally related by three sides of a right triangle in the mathematical relationship shown in equation 2.

$$S^2 = P^2 + Q^2 \qquad (2)$$

The quantities for real power P, reactive power Q and apparent power S were defined for single phase AC power. More commonly, power is supplied and utilized as three phase and the above formulas are modified by a √ multiplication factor and current and voltage are taken to be the line RMS quantities. The three phase apparent power is shown below where the RMS subscript is dropped and considered to be understood.

Power factor correction capacitors tend to draw a leading current and therefore, correct the lagging current from the inductive loads. Power factor correction capacitors can only correct the displacement power factor and do not mitigate the harmonic currents and associated reduction in power factor due to distortion factor. Power factor correction capacitors are costly, require maintenance and ultimately have a shelf life so it is more desirable to design the system to have a maximum power factor to begin with. A method to have high power factor (near unity) and the ability to quickly change voltage levels is the use of solid state on-load tap changers using power electronic devices [7]. On-load tap changers work in conjunction with a transformer consisting of multiple transformer taps (as many taps as desired can be used considering practical design constraints) to apply transformer taps with different voltages across the load through the switching of the power electronics. The voltage to the load would be applied in discrete steps determined by the transformer taps. In order to provide a continuously variable output voltage to a load, the electronic on-load tap changing methodology can be combined with firing angle control such as was used for the light dimmer. In such a configuration, the output voltage can be varied continuously between any pair of transformer voltage taps. Industrial power controllers utilizing electronic devices similar to the light dimmer often need to be able to provide a continuously variable output voltage and it is common to include additional voltage taps.

II. METHOD FOR IMPROVING POWER FACTOR AND ENERGY EFFICIENCY

Almost all design requires compromise of one sort or another. As an example, to have an improvement in efficiency for an electric motor at rated conditions usually requires a sacrifice elsewhere. Depending on the process characteristics, if it is desired to have a higher average efficiency for a range of operation, a design compromise may need to be made that reduces the efficiency at full loading. An electric motor design is just one example of design compromise and almost all engineering system design requires such compromises to be made.

To demonstrate the general concept of utilizing design compromise for achieving a desired goal, assume the system shown Figure 2.1 is controlling a 3 hour industrial process requiring electrical power for heating with the following approximate load requirements outlined in Figure 4. It is not important to focus on the particular electrical design as was shown in Figure 3, the electrical system could be a motor driving a mechanical load, transformer, electric heater, etc.

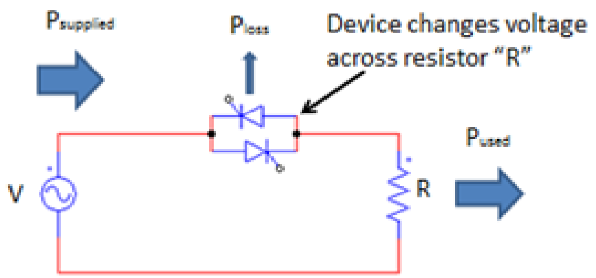

Figure 3: Power Flow and Delivery

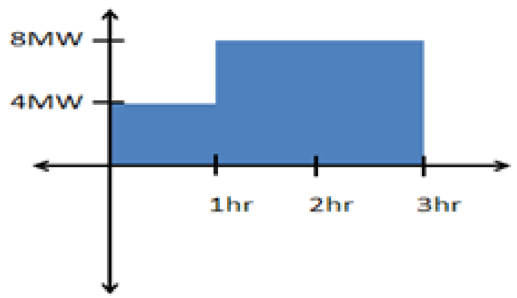

Figure 4: Process Load Characteristics

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The total energy utilized for the process is calculated and the results shown in Table 1. As can be seen from the table, more energy is used during hours 2 and 3 due to the increased time as well as the higher power requirements during that portion of the process. Recall that power is the rate of energy usage.

Table 1: Net Energy Consumed for Process with 80% Efficiency

Energy consumed by load during hour 1	4 MWh
Energy consumed by load during hour 2 and 3	8 MW*2hr = 16 MWh
Total Process Energy Consumed	4 + 16 = 20 MWh
Energy supplied during hour 1	(4M/0.8)(1hr) = 5 MWh
Energy supplied during hour 2 and 3	(8MW/0.8)(2hr) = (10MW)2hr) = 20 MWh
Total Energy Supplied	5 + 20 = 25 MWh
Average Energy Efficiency	20/25 = 80%

Similar to efficiency, power quality parameters such as power factor and harmonic distortion can be optimized for a process. The simplified examples described for energy efficiency will now be extended to power factor. Assume the same 3 hour industrial process with the same load characteristics of Figure 4 is now supplied by electrical equipment that has very high energy efficiency but reduced power factor. The system is shown below in Figure 5.

Similar to the energy efficiency example, assume the design has a maximum *power factor* of 0.8 which applies for the range of load conditions. Table 2 identifies the reactive power requirements computed from equation

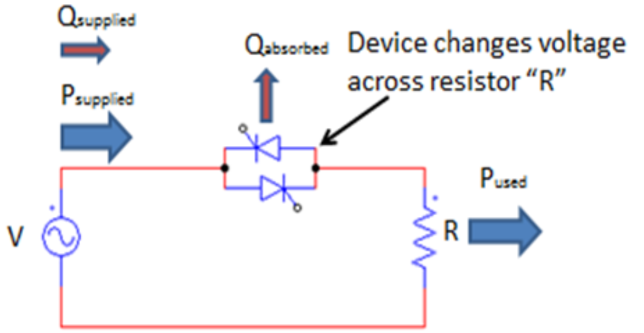

Figure 5: Power and Reactive Power Delivery

Table 2: Real and Reactive Power Required by the Process Load

Real Power (P)		Reactive Power (Q)
Hour 1	4 MW	3 MVAR
Hour 2 and 3	8 MW	6 MVAR

A. Design Optimization Summary

Processes or load cycles with variable conditions that repeat over time (i.e. voltage and power) can further be improved for maximizing power factor (or energy efficiency) during the design process. A math model must be developed for power factor as a function of system design constraints (i.e. transformer taps voltages and load voltage). If process conditions are known for how power and voltage change with time, a computer algorithm can be written to perform computations to maximize average power factor. Applying an algorithm approach to improving design provides the proper weighting of variables and can result in substantial improvement in average power factor for complex load characteristics. If the average power factor is improved for a single system, a plant operating with many systems will have an improved power factor and the more systems operating in the plant, the power factor will approach the average value computed for a single system. Additionally, the more systems operating in the plant, the plant deviations from the average value of the single system will be smaller. Since many processes may not repeat exactly, analyzing statistical data can be used to provide information relative to how the system typically varies.

III. ECONOMIC EVALUATION

Assume the industrial plant has an average of 20 MW of loads that are operating throughout the year that have reduced *power factor*. The above number is a reasonable number for a large processing plant and the total connected load could be much higher depending on the size of the plant and the type of process. The numbers chosen are only to get a sense of potential cost savings, however, the detailed economics must be applied to the specific situation being evaluated. The plant energy costs are computed from the below equations.

$$\text{Energy} = (P)(t) \tag{3.1}$$

$$\text{Energy Costs} = (\text{Energy})(\text{rate}) \tag{3.2}$$

For the example provided, the total energy cost is as follows (it should also be noted that the number is reasonable for a large process plant and could be much higher

Energy Cost = (20,000 kW)(8760 h/year)($0.10/(kWh)) = $17.5 million/year

The 3 transformer designs identified will be compared to get a sense for the potential annual savings. It is important to note, however, that the design examples analyzed were only to show the advantage of an algorithm approach and much more complex processes may have a much higher improvement. The *power factor* for the three designs is shown below in Table 3 for comparison.

Table 3: Transformer Designs for Economic Comparison

Transformer Design 1	Transformer Design 2	Transformer Design 3
Voltage taps: 13.8 kV, 5.3 kV, 2 kV	Voltage taps: 13.8 kV, 8 kV, 2 kV	Voltage taps: 13.8kV, 10.8 kV, 2.3 kV
Average power factor = 0.903	Average power factor = 0.938	Average power factor = 0.971

For charges directly based on kVAh, the annual utility bill is computed as follows:

Annual Savings = (Energy charges)(1/pfinitial – 1/pfimproved)

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The annual savings is applied to the 3 transformer designs as follows:

1) Transformer Design 2 to that of *Transformer Design 1*

The *power factor* was improved from 0.903-0.938. The savings would be as follows:

Annual Savings = ($17.5 million/year)(1/0.903 – 1/0.938) = **$723,000/year**

2) Transformer Design 3 to that of *Transformer Design 2* the *power factor* was improved from 0.938-0.971. The savings would be as follows:

Annual Savings = ($17.5 million/year)(1/0.938 – 1/0.971) = **$634,000/year**.

3) Transformer Design 3 to that of *Transformer Design 1* the *power factor* was improved from 0.903-0.971. The savings would be as follows:

Annual Savings = ($17.5 million/year)(1/0.903 – 1/0.971) = **$1.36 million/year**.

The above examples help provide an idea of potential savings for a small improvement in *power factor*. It must be considered, however, that more complex processes can have even more substantial improvement than the examples discussed. The improvement may be the difference between the customer being charged a hefty fee or not. Regardless of the fee schedule that is applied, any improvement in *power factor* will reduce transmission losses, improve voltage regulation and reduce equipment sizing, all of which does cost the utility more and there are no guarantees that *power factor* fee schedules will remain fixed at where they are today. In addition to optimizing designs for improved *power factor* during the design stage, return on investment (ROI) calculations should be performed on older equipment designs to assess the potential savings for replacing equipment.

IV. SUMMARY AND CONCLUSIONS

Electrical power systems are used to convert and transport energy over long distances where it can be reconverted in the form of mechanical energy (via electric motors) or heat (via electric heaters) or other possible forms for the end user at locations remote from the source. The electrical power system has the advantage of being able to transport energy over large distances relatively efficiently. The term *power* is used more frequently, however, it is important to understand that *power* is the rate of energy usage (energy/time). An example of a ton of coal was utilized to represent a given amount of energy and higher power usage will dictate how quickly that ton of coal is used up.

The purpose of the electrical generation, transmission and distribution system is to transport energy so that it can be used by the end user (industrial, commercial or residential). Although the end user primarily charged for the energy they consume (kWh), they indirectly pay for other costs such as capital costs of equipment, labor, etc. The way the end user uses the power supplied to them can create additional complications and costs for the electrical utility and those complications are generally captured with the term *power quality*. Although there are a number issues under the umbrella term *power quality*, two specific related *power quality* terms, *power factor* and *total harmonic distortion* were defined and their negative effects discussed. Improving *power quality* such as improved *power factor* and *total harmonic distortion* has the following benefits:

1) Improve energy transmission efficiency by reducing system losses
2) Improve voltage regulation
3) Free system capacity
4) Improved system security
5) Decrease costs by reducing equipment size

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