Enhancing Energy Efficiency with Power Factor Correction and Variable Speed

Taha Abdulwahid MAHMOOD
Department of Electrical Engineering
University of Kirkuk
Kirkuk, Iraq
taha-abdulwahid@uokirkuk.edu.iq

***Abstract*— This research examines the issues that arise from using certain methods to reduce energy waste in industrial applications, and proposes solutions to address them. First, it highlights the problems caused by the use of power factor improvement capacitors in electrical systems with extraneous (harmonic) voltages, identifies the underlying causes, and then suggests solutions to these issues. Second, it emphasizes the need to expand the use of variable speed drives to minimize the waste of electrical energy and achieve resulting economic savings. The use of synchronous motors whose speed is controlled by changing the supply source through attached converters is highly suitable for applications involving pumps, fans, compressors, mixers, and motors with high initial torque loads. The research then evaluates the merits of this approach. The significant technological advancements in the field of high-efficiency speed control of synchronous motors across a wide range of speeds and high-capacity applications, which emerged in the wake of the global energy crisis, have made this technology desirable for industrial applications, particularly in the area of energy storage.**

Keywords*— *control, energy efficiency, harmonic reduction, Power factor improvement, Synchronous motors.

I. INTRODUCTION

The world is witnessing many rapid and progressive changes in many aspects, including the field of generalization in all fields, including the field of information technology. The field of information technology is developing rapidly and extensively in all fields, including general general generalization and technical generalization. in particular, as it is directly related to the labor market, we are living in an environment that is characterized by a great deal of cooperation in various fields [1]. This is due to the accelerated progress in various fields, where competition has begun to exert pressure on organizations in all sectors.societies today are characterized by constant change as a result of technological, social and economic developments and economic and knowledge developments; this is the reason why today's societies are characterized by constant change as a result of technological, social, economic and knowledge developments [2]. Power factor adjustment is a method for increasing the efficiency of power utilization in electrical systems. Adjusting the power factor of electrical loads to get it closer to unity reduces the amount of reactive power in the system [3]. This not only decreases the overall use of energy, but also cuts demand charges paid by utility providers on industrial clients for wasteful energy use [4]. Power factor correction is a basic method for improving energy efficiency in electrical systems. The power factor measures how efficiently electrical power is used; a low power factor indicates that a considerable percentage of the electricity is not utilized, primarily as reactive power. Reactive power does not accomplish any meaningful work, but it is required for the operation of some types of electrical equipment, such as motors and transformers [5]. Excessive reactive power, on the other hand, can raise demand on the electrical supply, increase energy consumption, and cause greater distribution system losses [6]. Variable speed drives offer a distinct approach to energy efficiency by enabling precise control over motor speeds. In numerous industrial applications, motors often operate at a constant speed, regardless of the actual load demands . This can result in energy waste, especially when the motor is running at full speed while the load requirement is low [7]. VSDs address this issue by adjusting the motor speed to match the load requirements, ensuring that the motor only consumes the necessary energy for the task at hand [8]. The integration of power factor correction and variable speed drives into energy management practices offers a comprehensive approach to enhancing energy efficiency [9]. While each method provides unique benefits, their combined application can lead to even greater improvements in energy performance. Together, these technologies can contribute to substantial energy savings, reduced operational costs, and improved system reliability [10]. This paper deals with the issue of energy waste in industrial applications from two aspects. The first aspect highlights the use of power factor optimization capacitors in electrical systems to save energy and the issues arising from their use, and the second aspect highlights the benefits of expanding the use of variable speed synchronous motors to save energy from waste and the issues arising from their use as well. Through the research, we see that there is a correlation in the most important issues arising from the two mentioned aspects due to their applications in industry.

II. THE MAIN ASPECTS OF MOTOR SELECTION

Selecting the right motor for an industrial or commercial application is a critical decision that can significantly impact energy efficiency, operational costs, and equipment longevity. The process of motor selection involves evaluating a variety of factors to ensure that the chosen motor meets the specific requirements of the application while also contributing to overall energy conservation. Below are the main aspects to consider when selecting a motor:

A. Basic elements

1. Torque

The key factors that influence the selection of motors are the output power, speed, voltage, and most importantly, the torque (power divided by speed). These parameters determine the final size of the motor. For instance, a 1000 kW motor operating at 1500 rpm can be roughly the same size as a 500 kW motor running at 750 rpm. This allows for the creation of motors with different speed-power ratios but equivalent output power. Generally, the smaller the motor's diameter, the more cost-effective it is to manufacture.

2. Variable Speed Capability

The speed range and speed-to-torque relationship of the load are essential considerations when using variable speed drives. AC motors that must maintain constant torque across a wide speed range generally have a larger physical size compared to motors that only need to operate over a narrower speed range.

3. Voltage

In general, motors with greater power output tend to also have higher operating voltages, see Table 1.

Table I. The relationship between engine power and voltage

Voltage (Kv)	Min Output (Kw)	Normal Outputs		Max Output (Kw)
		Min (Kw)	Max (Kw)	
15	1000	1500	12000	15000
13.2	750	1000	10000	14000
11	500	750	8000	10000
6.6	200	500	4000	6000
3.3	100	200	2000	3000
0.66	-	0.1	500	750
0.44	-	0.1	400	600

B. Startup Procedures

One of the easiest common methods for starting AC motors is the direct method (D.O.L). To ensure the success of this method, the power source must be capable of absorbing the high starting current of (4-6) times the maximum load current in medium-sized motors. High starting currents have many negative effects on motors, while most types of motors in circulation do not require such a current to start, i.e. they have small starting torques, such as pumps, fans, compressors, cranes (Extruder Drives), high-speed and high-power motors, and starters (for generators and gas turbines, etc.). Among the negative effects of high starting currents on motors, in addition to being a waste of energy, they cause rapid heating of the motor coils, which requires the use of coils with a high thermal capacity. They also impose a transient force (Transient Forces) on the end of the coils, which reaches 300 N.m in some medium-power motors, which reduces the life of the typical machine (20 years). These disadvantages are avoided by using variable speed motors in addition to saving the wasted starting energy due to the high starting current when not in use.

A common method in the industry is to use Converters to control the speed of synchronous motors by changing the frequency of the mains supply. They are also used as soft starters for limiting and scaling high starting current and for short start-up periods until the motor speed reaches synchronous speed. These converters are also an additional cost added to the cost of the motor, but it is possible to use one converter to start several motors by switching from the (Running Busbar) to the Starting Busbar, as shown in Figure 1, which shows the (Starting Busbar) for two machines.

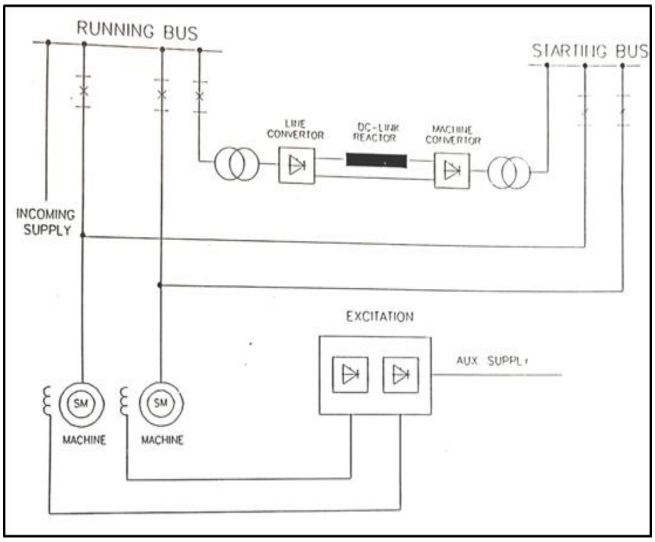

Fig.1. Single line diagram for soft-starting of two machines

Figure 2. shows the basic elements that make up variable speed synchronous motors that are currently in common use in the global industry and are available in capacities from 1000 to 30,000 kilowatts and can reach speeds up to 6500 rpm in some types (Turbo-Machine).

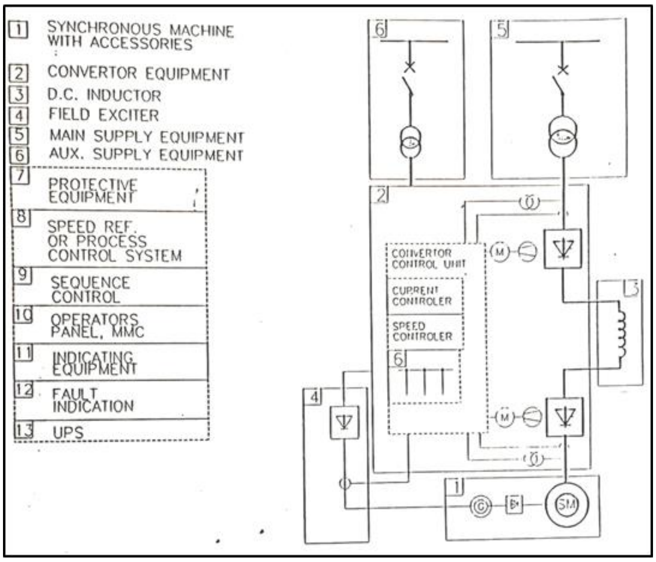

Fig.2. Block diagram of the drive system.

C. Efficiency and Cost

Motors are often selected on the basis of comparing low-cost and high-cost motors with high efficiency. It is known that the cost of energy consumption (electrical unit) varies from place to place, but it all depends on:

1- (Kw-HER) the power consumed.
2- (Kw-HER) which depends on the power consumed and the power factor.
3- Maximum Demand.

The electrical energy consumption of motors is obtained by knowing the effective (useful) power output and by knowing the losses, and the latter should be taken as an important criterion when comparing different motors. The total losses are particularly important when comparing variable speed motors with other methods of control and energy conservation such as controlling the angle of the blades in ventilation motors or eddy current inverters, as these latter methods of control and others result in energy losses and wastage whenever the recording limits of the motors are far from their design capacities (Rated Output).

This issue is overcome by variable speed drives that give high efficiency at all speeds and save on energy wastage and costs, and the maintenance costs of these motors and accessories are minimal compared to the energy savings, the losses mentioned above, over the life of the motor, which is typically 20 years.

If two motors differ in cost by (P) dollars and also differ in annual operating cost by (C) dollars, then if we assume the tariff class or unit energy consumption cost (R), we see that the total costs plus operating costs for (N) years are equal:

$$R = \frac{C}{P}\,[1 - \frac{1}{(1+R)^N}] \qquad (1)$$

D. Braking

Quick stopping of motors is the future goal of normal operation and keeps energy from being wasted and costly. There are many known methods of stopping in motors, including mechanical and electrical, and the latter is the most common, and this is done either by reversing phase rotation or dynamically by connecting resistors between the motor terminals, and these methods often impose great stresses on the machinery. Variable speed drives can be configured to give a controlled generative stop, and the importance of this is evident in motors with frequent stops, this method is preferred because the kinetic energy of the machine will be returned to the processing system or processing source during the stop period, resulting in reduced energy consumption.

E. General benefits of using variable speed drives

The use of variable speed drives using simple ratios, in addition to the goal of saving energy expended under load variables (pressure and flow), pressure and flow and their economic returns, achieves the following goals:

- High efficiency under all load conditions.
- High reliability, especially if simple rates are chosen.
- Maintenance-free Static Converters, especially if the synchronous motors are Brushless Type Exciter, thanks to the high starting current limitation that also protects the load from Mechanical Wear
- Suitable for use in hazardous areas.
- Startup is controlled and easy.
- The speed can be controlled from (50-100)% of the design speed in most types.
- Not affected by very short power outages.
- Low noise.

III. Power Factor

The simplest definition of power factor is the ratio of the current supplied as active power in an alternating current circuit and the residual current that does not fulfill its function (inactive power), as follows:

$$\frac{P}{S} = \frac{\text{Effective capacity}}{\text{Total capacity}} \qquad (2)$$

A coefficient of 0.8 for an electric motor means that 80% of the motor's current at maximum load is power to do work, 20% of the current is wasted energy, and the current meter will register the full percentage of the full current 100%. It is also known to optimize the power factor is for the purpose of reducing inefficient capacities in electrical distribution systems and results in:

1- Reducing the cost of purchased energy and saving energy from being wasted.
2- Release the sting of the electrical system.
3- Optimizing the voltage.

4- Reduce system losses.

There are common ways to optimize the power factor by using capacitors for low power factor loads. However, the effects of extraneous currents on the power factor can only be optimized by absorbing and separating them. As it is known that it is not possible to directly acknowledge what can be applied to improve the power factor on continuous motors operating on thyrestors circuits (also in variable speed motors), Figure 3. shows the path (Locus) of the alternating current vector (Vector) of a thyrestors motor with a fixed excitation circuit and 500 hp, whose speed varies from 100% to 10% under the maximum torque condition. This motor needs about 150 kV of power factor optimization capacitors at high speed to have a power factor value of 95% (0.95) different.

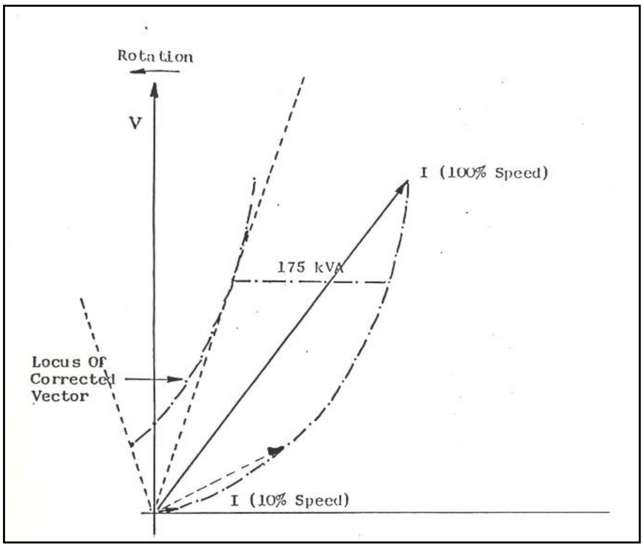

Fig.3. Locus of current vector

However, when the speed is reduced to 40%, the power factor is too low, so the power factor optimizers must be approximately 450 kV. The solution to this issue is to use capacitors, i.e. selecting capacitors with certain capacities that are then automatically inserted into the circuit through the power factor sensor. Before applying this, there are some questions that need to be answered first:

1- Is it necessary to always reduce the speed to 10%.

2- What is the expected speed during operation.

3- Is over-optimization to an advanced power factor permissible under certain speeds.

4- What are the speed and torque characteristics of the load.

For example, a 400 kV single-phase power factor capacitor that improves the power factor to 0.95 advanced below maximum speed, can give an improved power factor of 0.95 late down to 45% of speed without adding any complexity to locking the capacitors in series. Power factor improvers create two problems with DC thyristors in this area. The first is the problem of harmonics generated by the thyristor converters, which causes high intrusive currents to pass through the capacitors unless series reactors are used, which increases the cost. Therefore, the intrusive current system must be analyzed on site before installing the capacitors. The second problem occurs in fan motors, where Cube Law, the coupled power characteristics, and the (Near linear P.F.C/C) characteristics sometimes make it difficult to limit and determine the power factor within narrow ranges except by using capacitors with continuously variable capacitance or by inserting and removing a number of capacitors in series, as we mentioned earlier. Optimizing the power factor for factory and plant projects will save large direct sums and it seems feasible and in general it adds sums to the cost of the projects as well, and the cost of medium voltage capacitors per kilovar is lower than low pressure capacitors and is taken into account in the economic trade-offs. It is economically attractive to reduce the costs of energy expenditures and system capacity release by using power factor optimizers. Figure 4. shows the power factor for electrical substation equipment costing (S) and capacitors costing (C) on an equal installation base.

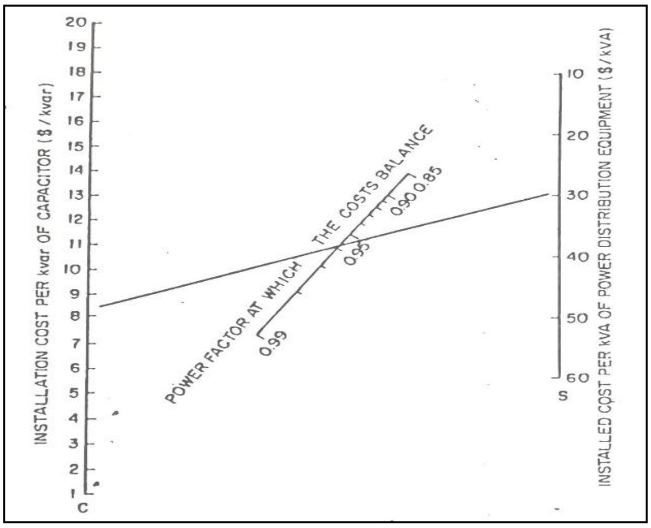

Fig.4. Nomogram for determining cost balance for Power Factor improvement

We view relative cost (S/C) values as essential in discovering economic utilization. For some applications, a power factor of 90% or 95% is prescribed. The ideal solution is to optimize the power factor levels here by combining the engineering sense of the efficiency of the operational system with the business sense of cost savings and investment. The use of capacitors to improve the power factor will reduce the inefficient power in the system, and it is preferable to place the capacitors as close to the load as practicable. Figure 5. shows four locations for installing capacitors, C1 is preferred, then C2 comes second, then C3 and finally C4, economic issues must also be considered when choosing the location of the capacitors, such as the cost of disconnecting and closing switches for capacitors and sensors, for example.

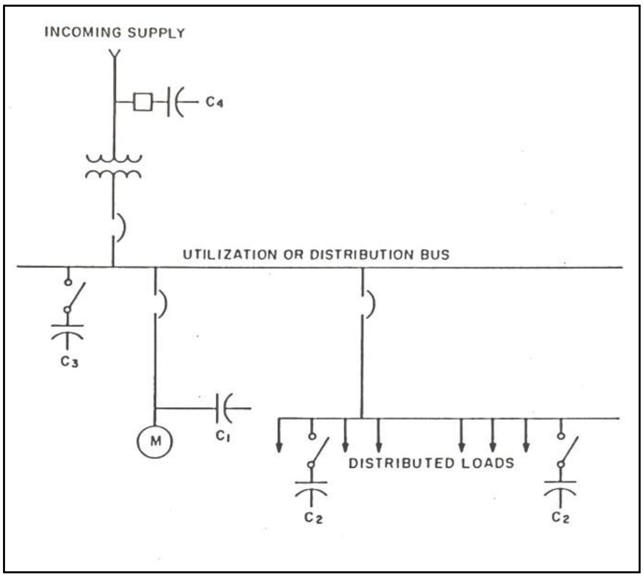

Fig.5. Possible shunt capacitor locations

Table 2. Shows the multiplication factor to determine the capacity improvement. For example, if we want to find the required capacitance value (Capacitor Rating) to improve the power factor of a 500 kW load from 76% to 93%, we apply the following equation:

KVAR = Kw * Multiplier
= 0.46 * 500
= 230.

Table II. Kw multipliers to determine reactive – power requirement for power factor improvement

Original Power Factor	Corrected Power Factor																		
	0.80	0.81	0.82	0.83	0.84	0.85	0.86	0.87	0.88	0.89	0.90	0.91	0.92	0.93	0.94	0.96	0.98	0.99	1.0
0.50	0.982	1.008	1.034	1.060	1.086	1.112	1.139	1.165	1.192	1.276	1.306	1.337	1.369	1.403	1.440	1.481	1.529	1.589	1.732
0.51	0.937	0.962	0.989	1.015	1.060	1.086	1.112	1.139	1.165	1.192	1.261	1.280	1.314	1.324	1.395	1.436	1.484	1.544	1.687
0.52	0.893	0.919	0.945	0.971	1.015	1.060	1.086	1.112	1.139	1.165	1.192	1.484	1.484	1.484	1.484	1.420	1.475	1.484	1.643
0.53	0850	0.876	0.902	0.928	0.971	1.015	1.060	1.086	1.112	1.139	1.165	1.369	1.369	1.369	1.369	1.369	1.369	1.369	1.600
0.54	0.809	0.835	0.861	0.887	0.928	0.971	1.015	1.060	1.086	1.112	1.139	1.306	1.192	1.306	1.306	1.306	1.306	1.306	1.559
0.55	0.769	0.795	0.821	0.847	0.887	0.928	0.971	1.015	1.060	1.086	1.112	1.276	1.165	1.192	1.276	1.276	1.276	1.276	1.480
0.56	0.730	0.756	0.782	0.808	0.847	0.887	0.928	0.971	1.015	1.060	1.086	1.165	1.139	1.165	1.192	1.165	1.165	1.165	1.442
0.57	0.692	0.718	0.744	0.770	0.808	0.847	0.887	0.928	0.971	1.015	1.060	1.139	1.112	1.139	1.165	1.192	1.139	1.139	1.333
0.58	0.655	0.681	0.707	0.733	0.770	0.808	0.847	0.887	0.928	0.971	1.015	1.060	1.086	1.112	1.139	1.165	1.192	1.165	1.233
0.59	0.619	0.645	0.671	0.697	0.733	0.770	0.808	0.847	0.887	0.928	0.971	1.015	1.060	1.086	1.112	1.139	1.165	1.192	**1.201**
0.60	0.583	0.609	0.635	0.661	0.697	0.733	0.770	0.808	0.847	0.887	0.928	0.971	1.015	1.060	1.086	1.112	1.139	1.165	1.192
0.61	0.549	0.575	0.601	0.627	0.661	0.697	0.733	0.770	0.808	0.847	0.887	0.928	0.971	1.015	1.060	1.086	1.112	1.139	1.165
0.62	0.516	0.542	0.568	0.594	0.627	0.661	0.697	0.733	0.770	0.808	0.847	0.887	0.928	0.971	1.015	1.060	1.086	1.112	1.139
0.63	0.483	0.509	0.535	0.561	0.594	0.627	0.661	0.697	0.733	0.770	0.808	0.847	0.887	0.928	0.971	1.015	1.060	1.086	1.112
0.64	0.451	0.474	0.503	0.529	0.561	0.594	0.627	0.661	0.697	0.733	0.770	0.808	0.847	0.887	0.928	0.971	1.015	1.060	1.086
0.65	0.419	0.445	0.471	0.497	0.529	0.561	0.594	0.627	0.661	0.697	0.733	0.770	0.808	0.847	0.887	0.928	0.971	1.015	1.060
0.66	0.388	0.414	0.445	0.466	0.497	0.529	0.561	0.594	0.627	0.661	0.697	0.733	0.770	0.808	0.847	0.887	0.928	0.971	1.015
0.67	0.358	0.384	0.410	0.436	0.466	0.497	0.529	0.561	0.594	0.627	0.661	0.697	0.733	0.770	0.808	0.847	0.887	0.928	0.971
0.68	0.328	0.354	0.380	0.406	0.436	0.466	0.497	0.529	0.561	0.594	0.627	0.661	0.697	0.733	0.770	0.808	0.847	0.887	0.928
0.69	0.299	0.325	0.351	0.377	0.406	0.436	0.466	0.497	0.529	0.561	0.594	0.627	0.661	0.697	0.733	0.770	0.808	0.847	0.887
0.70	0.270	0.296	0.322	0.348	0.377	0.406	0.436	0.466	0.497	0.529	0.561	0.594	0.627	0.661	0.697	0.733	0.770	0.808	0.847
0.71	0.242	0.268	0.294	0.320	0.348	0.377	0.406	0.436	0.466	0.497	0.529	0.561	0.594	0.627	0.661	0.697	0.733	0.770	0.808
0.72	0.214	0.240	0.266	0.292	0.320	0.348	0.377	0.406	0.436	0.466	0.497	0.529	0.561	0.594	0.627	0.661	0.697	0.733	0.770
0.73	0.186	0.212	0.238	0.264	0.292	0.320	0.348	0.377	0.406	0.436	0.466	0.497	0.529	0.561	0.594	0.627	0.661	0.697	0.733
0.74	0.159	0.185	0.211	0.237	0.264	0.292	0.320	0.348	0.377	0.406	0.436	0.466	0.497	0.529	0.561	0.594	0.627	0.661	0.697
0.75	0.132	0.158	0.184	0.210	0.237	0.264	0.292	0.320	0.348	0.377	0.406	0.436	0.466	0.497	0.529	0.561	0.594	0.627	0.661
0.76	0.105	0.131	0.157	0.183	0.210	0.237	0.264	0.292	0.320	0.348	0.377	0.406	0.436	0.466	0.497	0.529	0.561	0.594	0.627
0.77	0.079	0.105	0.131	0.157	0.183	0.210	0.237	0.264	0.292	0.320	0.348	0.377	0.406	0.436	0.466	0.497	0.529	0.561	0.594
0.78	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.237	0.264	0.292	0.320	0.348	0.377	0.406	0.436	0.466	0.497	0.529	0.561
0.79	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.237	0.264	0.292	0.320	0.348	0.377	0.406	0.436	0.466	0.497	0.529
0.80	0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.237	0.264	0.292	0.320	0.348	0.377	0.406	0.436	0.466	0.497
0.81		0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.237	0.264	0.292	0.320	0.348	0.377	0.406	0.436	0.466
0.82			0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.237	0.264	0.292	0.320	0.348	0.377	0.406	0.436
0.83				0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.237	0.264	0.292	0.320	0.348	0.377	0.406
0.84					0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.237	0.264	0.292	0.320	0.348	0.377
0.85						0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.237	0.264	0.292	0.320	0.348
0.86							0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.237	0.264	0.292	0.320
0.87								0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.237	0.264	0.292
0.88									0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.237	0.264
0.89										0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.237
0.91											0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210
0.92												0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183
0.93													0.000	0.026	0.052	0.078	0.104	0.130	0.157
0.94														0.000	0.026	0.052	0.078	0.104	0.130
0.95															0.000	0.026	0.052	0.078	0.104
0.96																0.000	0.026	0.052	0.078
0.97																	0.000	0.026	0.052
0.98																		0.000	0.026
0.99																			0.000

IV. Harmonic Currents

Harmonic currents are generated from the use of Static Converters for speed control as well as from the use of capacitor controllers to optimize the power factor. These currents, as is known, generate efforts in the equivalent resistance of the supply source (Supply Impedance), and these efforts are reflected on all loads associated with the source, and their increase leads to interference in electronic devices, especially electronic computers and communication devices, and causes increased heating of the power factor improvement capacitors, and these currents cause heating of the motor coils themselves as well, and cannot be converted into energy or effective torque, in addition to its negative impact on the quality of the waveform described in the measurements. The issue of these currents as a result of the use of thyristors in the mentioned devices and equipment, which generate these currents because they operate in switching mode, can be addressed by using several phases, for example (Pulse Convertor Fed From A 6 - Phase supply) instead of (6-Pulse) equipped from a triple source (3 Phase) as shown in Figure 6.

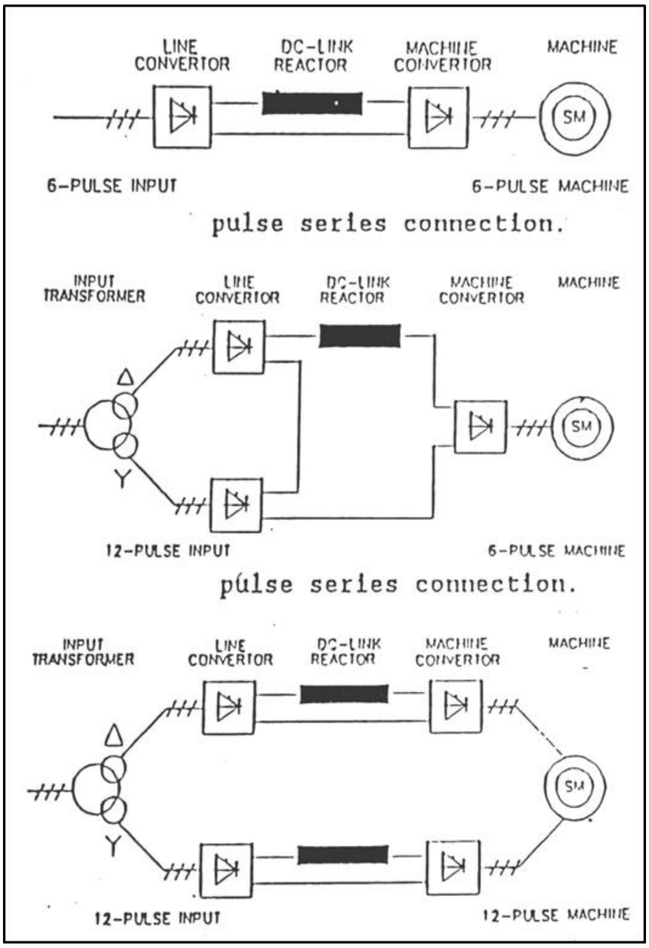

Fig. 6. Pulse parallel connection

V. Conclusion

The technical performance of controlled-speed synchronous motors is similar to that of DC motors, provided that the overall system's mechanical requirements are typical, with no significant load inertia or presence of mechanical resonant frequencies within the speed range. Research has shown that there are several key factors that play a role in the optimal selection of the machine type. We would like to emphasize the use of variable speed motors in most industrial applications. The savings achieved through energy conservation and the high efficiency of these motors, along with power factor improvements, depend on the one hand. On the other hand, the level of complexity in the electrical system they introduce requires objective engineering assessment and comparison. A clear specification of the requirements, along with discussions with the manufacturers of these motor types, who have ample facilities to address the negatives mentioned in the research, such as accurate measurement of harmonic currents, evaluation of operating systems, and adjustment of pulsating torques and harmonic frequencies using efficient ready-made software, will all shed light on the importance of expanding the use of variable speed motors and power factor improvement for energy conservation.

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