International Journal of Latest Technology in Engineering, Management & Applied Science (IJLTEMAS)
Volume VII, Issue XII, December 2018 | ISSN 2278-2540

Application of Synchronous Motor to Improve Power Factor for Industrial Loads

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***Abstract*— Most of the industrial loads such as induction motors are inductive in nature and hence have low lagging power factor. Around 60% of the utility load consists of motors and hence the overall power factor of the power system is low. The low power factor is highly undesirable as it causes an increase in current, resulting in additional losses of active power in all the elements of power system from power station generator down to the utilization devices. This paper describes the power factor can be improved by connecting the synchronous motor operated in an overexcited mode in parallel with the industrial loads operating at lagging power factor. The designed industrial load is 8 TPH rice milling plant consists of unity power factor loads 250 kW (lighting loads and other loads) and induction motor loads 350 kW, efficiency 96 % at power factor 0.7 lagging. In this paper, the appropriate rating of synchronous motor is selected to compensate the reactive power and improve the power factor of rice milling plant from 0.7 lagging to the region within 0.95 laggings and unity.**

***Keywords*—power factor, power factor improvement, lagging, leading, unity, synchronous motor, induction motor**

I. INTRODUCTION

Normally, the power factor of the whole load on a large generating station is in the region of 0.8 to 0.9. However, sometimes it is lower and is such case it is generally desirable to take special steps to improve the power factor. Low power factor can increase electricity generating costs, reduce electrical distribution capacity and increase voltage drop. Therefore, lower factor is undesirable from economic point of view. The low power factor is mainly due to the facts that most of the industrial loads are inductive and, therefore take lagging currents. In order to improve the power factor, synchronous motor equipment taking leading power should be connected in parallel with the load, it takes a leading current which partly neutralizes the lagging reactive component of the load. Application of synchronous motor as compensation equipment in a system has the following effects: (1) Reduction in reactive component of line current. (2) Maintenance of voltage profile within limit. (3) Reduction of I^2R losses in the line and other equipment due to reduction in current. (4) Reduction in investment in the system per kW of load supplied. (5) Decrease in kVA loading of generators, transformers and other equipments. This decrease in kVA loading may relieve an over load conditions or release capacity of load growth. (6) Reduction in kVA demand charges for large consumers. (7) Improvement in power factor of the system.

A. *Characteristic of synchronous motor*

In industry, synchronous motors are used mainly where a constant speed is desired. An important feature of a synchronous motor is that it can draw either lagging or leading reactive current from the ac supply system. In a synchronous motor, if the rotor field winding provides just the necessary excitation, the stator will draw no reactive current; that is, the motor will operate at a unity power factor. If the rotor excitation current is decreased, lagging reactive current will be drawn from the ac source to aid magnetization by the rotor field current, and the machine will operate at a lagging power factor. If the rotor field current is increased, leading reactive current will be drawn from the ac source to oppose magnetization by the rotor field current, and the machine will operate at a leading power factor. Thus, by changing the field current, the power factor of the synchronous motor can be controlled. If the motor is not loaded, but is simply floating on the ac supply system, it will thus behave as a variable inductor or capacitor as its rotor field current is changed. A synchronous machine with no load is called a synchronous condenser. It may be used in power transmission systems to regulate line voltage. In industry, synchronous motors are used with other induction motors and operated in an overexcited mode so that they draw leading current to compensate the lagging current drawn by the induction motors, thereby improving the overall plant power factor.

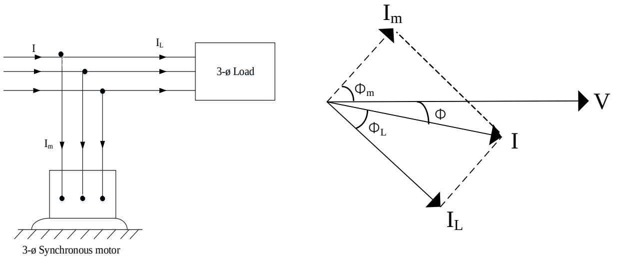


Fig.1 Power factor improvement by synchronous motor method

Fig.1 shows the power factor improvement by synchronous motor method. The three phase load takes current I_L at low lagging power factor cos Φ_L. The synchronous condenser takes a current Im which leads the voltage by an angle Φ_m. The resultant current I is the phasor sum of I_m and I_L and lags behind the voltage by an angle Φ. It is clear that Φ is less than Φ_L so that cos Φ is greater than cos Φ_L.Thus the power factor is increased from cos Φ_L to cos Φ.

B. Effect of Change of Excitation of Synchronous Motor

The terminal voltage *V* of a synchronous motor is constant. If the mechanical load is constant, a change in excitation (i.e. field current) causes a change in power factor, because the phasor relation between *E* and *V* (Fig.2) must be satisfied at all values of *E*. This characteristic of a synchronous motor makes it as a very suitable device for improvement of power factor is power systems. A constant applied voltage means a constant resultant flux. This resultant flux is due to the action of both dc source and ac source. If excitation is large, the field produced by rotor is too high. Consequently the armature mmf becomes magnetizing, so as to keep the resultant flux constant.

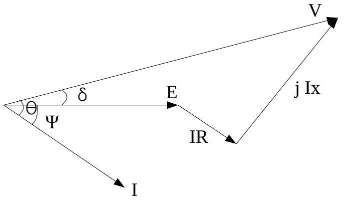


Fig.2 Phasor diagram of synchronous motor

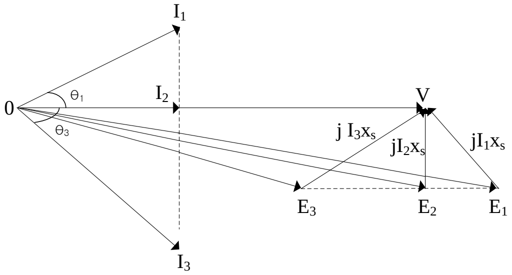
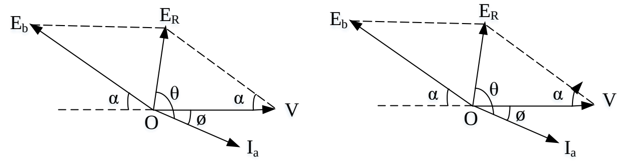


Fig.3 Effect of excitation on power factor of synchronous motor

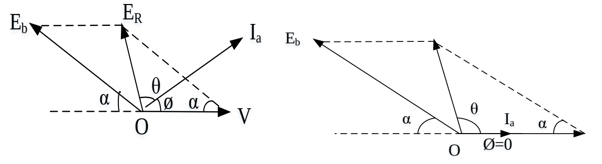
Fig. 3 shows the phasor diagram of a synchronous motor supplying a constant mechanical loat at three different values of excitation E_1, E_2 and E_3. The power developed is (3 VE/x_s) sin δ. As *E* changes, δ also changes, so as to keep the power developed at constant value. The locus on *E* is the dotted line. When emf is E_1 , the field flux is too high. The current I_1 is now at a leading power factor cos θ_1. The leading reactive current exerts a demagnetizing effect to restore the resultant flux to the constant value The phasor sum of E_1 and jI_1x_s gives the terminal voltage *V* (the armature resistance R_a has been neglected). When the excitation emf is E_2, there is no excess flux produced by the rotor winding. Therefore the input current I_2 has no reactive component and the power factor is 1. When the excitation voltage is E_3, the motor is under excited. The armature current now assumes the position I_3 and the power factor is lagging. The lagging current has a magnetizing effect, which helps to establish the air gap flux demanded by the terminal voltage. Thus an over excited synchronous motor operates at a leading power factor, where as an under excited one operates at a lagging power factor.

C. Synchronous motor with different excitations

A synchronous motor is said to have normal excitation when E_b =V. If field excitation is such that E_b < V, the motor is said to under-excited. In both these conditions, it has a if d.c field excitation is such that E_b > V, then motor is said to be over-excited and draws a leading current. Fig. 4 shows the different excitation conditions of synchronous motor.



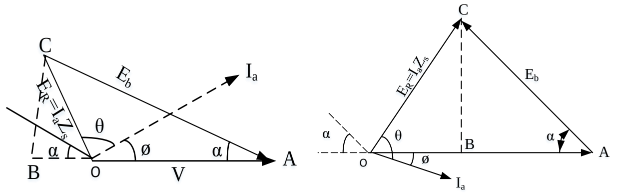
(a) Eb=V (lagging P.F) (b) Eb<V (lagging P.F)



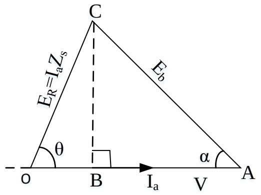
(c) Eb>V (leading P.F) (d) Eb>V (Unity P.F)

Fig.4 Synchronous motor with different excitation condition

There will be some value of excitation for which armature current will be in phase with V, so that power factor will become unity, as shown in Fig.4 (d). The value of ∞ and back e.m.f E_b can be found with the help of vector diagrams for various power factors as shown in Fig.5.



(a) Lagging P.F (b) Leading P.F



(c) Unity P.F

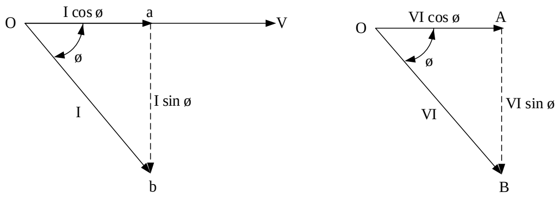
Fig.5 Power factor diagrams of Synchronous motor

II. POWER FACTOR IMPROVEMENT

A. *Power Factor and Power Triangle*

The cosine of angle between voltage and current in an a.c circuit is known as power factor. In an a.c circuit, there is generally a phase difference Φ between voltage and current. The term cos Φ is called the power factor of the circuit. If the circuit is inductive, the current lags behind the voltage and the power factor is referred to as lagging. However, in a capacitive circuit, current leads the voltage and power factor is said to be leading. Consider an inductive circuit taking a lagging current *I* from supply voltage *V*; the angle of lag being Φ. The phasor diagram of the circuit is shown in Figure.5. The circuit current *I* can be resolved into two perpendicular components; *I* cos Φ in phase with *V* and *I* sin Φ 90 Hout of phase with *V*. The *I* cos Φ is known as active or wattful component, where as component *I* sin Φ is called the reactive or wattles component. The reactive component is measure of the power factor. If the reactive component is small, the phase angle Φ is small and hence power factor cos Φ will be high. Therefore, a circuit having small reactive current *I* sin Φ will have high power factor and vice-versa.

The analysis of power factor can also made in terms of power drawn by the a.c circuit. If each side of the current triangle oab of Fig.6 (a) is multiplied by voltage *V*, then we get the power triangle *OAB* shown in Fig.6 (b).



(a)Phasor diagram (b) Power Triangle

Fig. 6 Phasor diagram and power triangle of the circuit

OA = *VI* cos Φ and represents the active power in kW

AB = *VI* sin Φ and represents the reactive power in kVAR

OB = *VI* and represents the apparent power in kVA

$$(\text{kVA})^2 = (\text{kW})^2 + (\text{kVAR})^2 \qquad (1)$$

$$\text{Cos } \Phi = \frac{\text{active power}}{\text{apparent power}} = \frac{\text{kW}}{\text{kVA}} \qquad (2)$$

$$\text{kVAR} = \text{kVA} \sin \Phi = \frac{\text{kW}}{\cos \Phi} \sin \Phi = \text{kW} \tan \Phi \qquad (3)$$

B. *Power Factor Correction*

The power factor correction can also be illustrated from power triangle. Thus referring to Fig.7, the power triangle *OAB* is for the power factor cos Φ_1, where as power triangle *OAC* is for the improved power factor cos Φ_2. It may be seen that active power (*OA*) does not change with power factor improvement. However, the lagging kVAR of the load is reduced by the power factor correction equipment, thus improving the power factor to cos Φ_2. Knowing the leading kVAR supplied by the power factor correction equipment, the desired results can be obtained.

Leading kVAR supplied by p.f correction equipment

$$= \text{kVAR}_1 - \text{kVAR}_2 \qquad (4)$$

$$= \text{kW} (\tan \Phi_1 - \tan \Phi_2) \qquad (5)$$

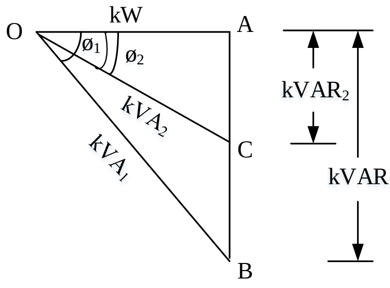


Fig.7 Power factor correction diagram

III. CASE STUDY OF POWER FACTOR IMPROVEMENT USING SYNCHRONOUS MOTOR

The following data are the required capacity of the designed industrial loads of 8 TPH rice milling plant. This rice milling plant loads are operated with full load.

(i) Lighting loads and others = 250 kW at unity p.f

(ii) Total Induction Motor loads = 350 kW, efficiency 96 % at p.f 0.7 lagging

In this case study, 160 kW, 180 kW, 200 kW, 225 kW and 250 kW of synchronous motor with efficiency 95 % are used to calculate and select the appropriate rating of synchronous motor to improve the power factor 0.7 to 0.95 lagging of rice milling plant. These various synchronous motors are considered at 0.75 leading, 0.8 leading, 0.85 leading, and 0.9 leading, 0.95 leading and unity power factor for 50%, 75%, 100% and 125% change of induction motor loads. The power factor of overall plant is limited within 0.95 lagging and unity.

Using the suffixes 1, 2 and 3 to indicate the different loads,

$$\text{kVA}_1 = \frac{\text{kW1}}{\cos \Phi 1} \quad \text{(for unity p.f load)} \qquad (6)$$

$$\text{kVA}_2 = \frac{\text{kW2}}{\cos \Phi 2} \quad \text{(for induction motor)} \qquad (7)$$

$$\text{kVA}_3 = \frac{\text{kW3}}{\cos \Phi 3} \quad \text{(for synchronous motor)} \qquad (8)$$

$$\text{kVAR}_1 = \text{kVA}_1 \text{ x } \sin \Phi_1 \quad \text{(for unity p.f load)} \qquad (9)$$

$$\text{kVAR}_2 = \text{kVA}_2 \text{ x } \sin \Phi_2 \quad \text{(for induction motor)} \qquad (10)$$

$$kVAR_3 = kVA_3 \times \sin \Phi_3 \quad \text{(for synchronous motor)} \qquad (11)$$

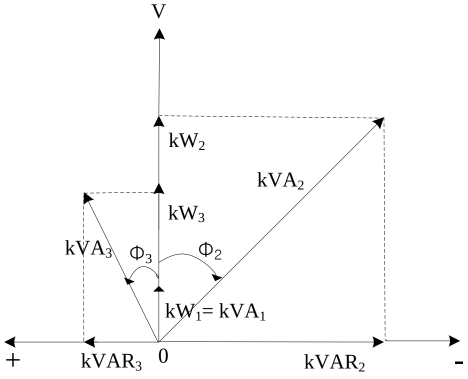


Fig. 8 Power factor improvement diagram for rice milling plant

These loads are represented in Fig.8. The three kVAs' are not in phase. In order to fine the total kVA, we resolve each kVA into rectangular components kW and kVAR as shown in Fig.6. The total kW and kVAR may then combine to obtain total kVA. $kVAR_2$ and $KVAR_3$ are in the opposite directions: $kVAR_2$ being a lagging while $kVAR_3$, being a leading kVAR.

TABLE I

PERCENTAGE OF INDUCTION MOTOR LOADS

% of I.M Load	Real Power (kW)	Reactive Power(kVAR)
50	182.5	186.178 (lag;)
75	273.75	278.267 (lag;)
100	365	372.356 (lag;)
125	456.75	465.445 (lag;)

TABLE II

CALCULATED RESULTS USING 160 KW SYNCHRONOUS MOTOR

% of I.M loads	p.f of synchronous motor					
	0.75 (lead)	08 (lead)	0.85 (lead)	0.9 (lead)	0.95 (lead)	1
50	0.998 (lag;)	0.995 (lag;)	0.990 (lag;)	0.985 (lag;)	0.977 (lag;)	0.955 (lag;)
75	0.983 (lag;)	0.976 (lag;)	0.969 (lag;)	0.961 (lag;)	0.951 (lag;)	0.927 (lag;)
100	0.961 (lag;)	0.954 (lag;)	0.946 (lag;)	0.937 (lag;)	0.926 (lag;)	0.903 (lag;)
125	0.940 (lag;)	0.932 (lag;)	0.924 (lag;)	0.916 (lag;)	0.905 (lag;)	0.803 (lag;)

TABLE III

CALCULATED RESULTS USING 180 KW SYNCHRONOUS MOTOR

% of I.M loads	p.f of synchronous motor					
	0.75 (lead)	08 (lead)	0.85 (lead)	0.9 (lead)	0.95 (lead)	1
50	0.999 (lag;)	0.998 (lag;)	0.994 (lag;)	0.989 (lag;)	0.980 (lag;)	0.958 (lag;)
75	0.988 (lag;)	0.982 (lag;)	0.976 (lag;)	0.967 (lag;)	0.957 (lag;)	0.932 (lag;)
100	0.969 (lag;)	0.961 (lag;)	0.953 (lag;)	0.944 (lag;)	0.933 (lag;)	0.908 (lag;)
125	0.949 (lag;)	0.940 (lag;)	0.932 (lag;)	0.923 (lag;)	0.912 (lag;)	0.888 (lag;)

TABLE IV

CALCULATED RESULTS USING 200 KW SYNCHRONOUS MOTOR

% of I.M loads	p.f of synchronous motor					
	0.75 (lead)	08 (lead)	0.85 (lead)	0.9 (lead)	0.95 (lead)	1
50	0.999 (lag;)	0.998 (lag;)	0.996 (lag;)	0.991 (lag;)	0.984 (lag;)	0.960 (lag;)
75	0.992 (lag;)	0.987 (lag;)	0.980 (lag;)	0.972 (lag;)	0.961 (lag;)	0.935 (lag;)
100	0.975 (lag;)	0.968 (lag;)	0.959 (lag;)	0.950 (lag;)	0.938 (lag;)	0.911 (lag;)
125	0.956 (lag;)	0.948 (lag;)	0.939 (lag;)	0.929 (lag;)	0.918 (lag;)	0.892 (lag;)

TABLE V

CALCULATED RESULTS USING 225 KW SYNCHRONOUS MOTOR

% of I.M loads	p.f of synchronous motor					
	0.75 (lead)	08 (lead)	0.85 (lead)	0.9 (lead)	0.95 (lead)	1
50	0.999 (led;)	0.999 (lag;)	0.998 (lag;)	0.995 (lag;)	0.987 (lag;)	0.963 (lag;)
75	0.996 (lag;)	0.991 (lag;)	0.985 (lag;)	0.978 (lag;)	0.967 (lag;)	0.939 (lag;)
100	0.982 (lag;)	0.975 (lag;)	0.967 (lag;)	0.957 (lag;)	0.945 (lag;)	0.916 (lag;)
125	0.965 (lag;)	0.957 (lag;)	0.948 (lag;)	0.937 (lag;)	0.925 (lag;)	0.896 (lag;)

TABLE VI

CALCULATED RESULTS USING 250 KW SYNCHRONOUS MOTOR

% of I.M loads	p.f of synchronous motor					
	0.75 (lead)	08 (lead)	0.85 (lead)	0.9 (lead)	0.95 (lead)	1
50	0.997 (led;)	0.999 (led;)	0.999 (lag;)	0.996 (lag;)	0.989 (lag;)	0.966 (lag;)
75	0.998 (lag;)	0.995 (lag;)	0.989 (lag;)	0.982 (lag;)	0.971 (lag;)	0.943 (lag;)
100	0.987 (lag;)	0.981 (lag;)	0.973 (lag;)	0.963 (lag;)	0.951 (lag;)	0.921 (lag;)
125	0.972 (lag;)	0.966 (lag;)	0.955 (lag;)	0.944 (lag;)	0.931 (lag;)	0.901 (lag;)

TABLE VII

COMPARISON RESULTS USING VARIOUS SYNCHRONOUS MOTOR

% of I.M load	The operating leading power factor of synchronous motor				
	160 kW	180 kW	200 kW	225 kW	250 kW
50	0.75 ~ 1	0.75 ~ 1	0.75 ~ 1	0.75 ~ 1	0.75 ~ 1
75	0.75 ~ 0.95	0.75 ~ 0.95	0.75 ~ 0.95	0.75 ~ 0.95	0.75 ~ 0.95
100	0.75 ~ 0.8	0.75 ~ 0.85	0.75 ~ 0.9	0.75 ~ 0.9	0.75 ~ 0.9
125	Below limited region	Below limited region	0.75	0.75~ 0.8	0.75~ 0.85

Using the equations, the result data are calculated as shown in Table II, III, IV, V and VI. The comparison results by using different ratings of synchronous motor are shown in Table VII. According to the results data, the power factor using the ratings of 225kW and 250kW synchronous motor are operating within the limit, but they are large and more cost. The range of power factor by using 200kW synchronous motor can operate the plant load changing within the limited region (0.95 lagging and unity). Therefore, the rating of 200kW synchronous motor is an appropriate motor for the power factor improvement of 8 TPH rice milling plant.

IV. CONCLUSION

In case of low power factor of the system, the system current will be increased and this high current of the system will cause to the large line losses (copper losses), the large kVA rating and size of electrical equipments, the greater conductor size and cost, the poor voltage regulation and large voltage drop, the low efficiency and penalty from electric power supply company. Therefore, power factor correction is becoming a greater concern for industrial and manufacturing plants all around the world.

In practice, the static capacitor, phase advancer and synchronous motor are mainly used as the load compensator. Generally, synchronous motor is used to improve the power factor in large industries because of synchronous motor has some advantages in comparison with others compensator. The power factor of a synchronous motor is controllable within its design and load limits. According to the results data, this paper show that the power factor of 8TPH rice milling plant for 50%, 75%, 100% and 125% change of induction motor loads can be improved from 0.7 lagging p.f to the limited region within 0.95 lagging and unity p.f when the plant loads are connected in parallel with the rating of 200kW synchronous motor at 0.75 leading, 0.8 leading, 0.85 leading, and 0.9 leading, 0.95 leading and unity power factor.

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