

The V-CURVE Analysis and Study of Synchronous Motors Using MATLAB program

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ABSTRACT

Today Synchronous motors are widely used in modern societies: industrial, commercial, agricultural, and domestic applications as constant-speed motors or as compensators for reactive power control in large power systems. Also understanding the machine's behaviour and determining its equivalent network and performance characteristics are of prime importance to a power engineer. This paper explains the constructional features and operating principles of the synchronous motor performance, the effects of load and field excitation on the synchronous motor are investigated. The V-curve of a synchronous machine is analysed, studied, and a review of various excitation systems provided. MATLAB program is used to verify this study.

Keywords: synchronous motor, over excitation, vector diagrams, V-curves.

Introduction

Synchronous motors are three phase AC motors which run at synchronous speed, without slip. Synchronous motors have the following characteristics [1]:

- A three-phase stator similar to that of an induction motor. Medium voltage stators are often used.
- A wound rotor-rotating field which has the same number of poles as the stator, and is supplied by an external source of direct current (DC). Both brush-type and brushless exciters are used to supply the DC field current to the rotor.

With the rotor at standstill and a three-phase voltage applied to the armature winding, the resultant rotating armature MMF moves past the rotor at synchronous velocity, producing an alternating torque with an average value of zero. The plain synchronous motor thus has no inherent starting torque. To start the motor, the following methods may be employed [1,2]:

- *Pony motor starting:*

Earlier machines were started using this method. A small directly coupled induction motor is used to drive the synchronous machine close to synchronous speed, and synchronizing is carried out by means of a

synchroscope. The induction motor usually has two poles fewer than the synchronous motor, and so is capable of raising the speed of the main motor to synchronous speed. This method is not convenient for industry applications.

- *Starting as an induction motor:* Modern machines are usually of self synchronizing type and are arranged to start as induction motors. The pole faces of the synchronous motor are fitted with a damper winding (similar to a partial squirrel cage winding). With the field winding open-circuited, the armature winding is connected to a reduced voltage provided by an autotransformer. The rotor accelerates by induction motor action and runs up to a speed slightly less than the synchronous speed. Excitation is then applied and synchronizing torque produced. Provided that the slip is not too large, the rotor will pull into synchronism.

Synchronous motors will run at synchronous speed in according to well known equation below [3],

$$\text{Synchronous-RPM} = (120 f/N) \dots (1)$$

Where,

f is Frequency & N is Number of Poles

When studying the effect of field excitation on motor performance, it is often assumed that the motor is loaded such that it draws a constant power from the supply. Since both the power and the voltage are constant, it follows that [4],

$$I_a \cos \Phi = I_a = \text{constant} \quad \dots(2)$$

Where I_a is the active component of armature current, and $I_a Z = \text{constant}$

Figure 1 shows the effect of change in field excitation on the operation of the synchronous motor. As the field current is changed, the tip of armature current phasor I will flow the locus XX (a line perpendicular to V), while the tip of the back EMF. Phasor E_f will flow the locus YY (a line perpendicular $I_2 Z_s$), where I_2 is the in-phase component of armature current. When the synchronous motor is initially overexcited and is operating at point 1 the corresponding armature current I_1 is leading V , and hence the input power factor is leading. Reduction of field current causes the tip of E_f phasor to move towards point 2: the armature current decreases to a minimum (I_2) and the motor input power factor increases to unity. Further reduction of field current causes E_f to move to point 3: the armature current increases to I_3 , and the input power factor becomes lagging [5].

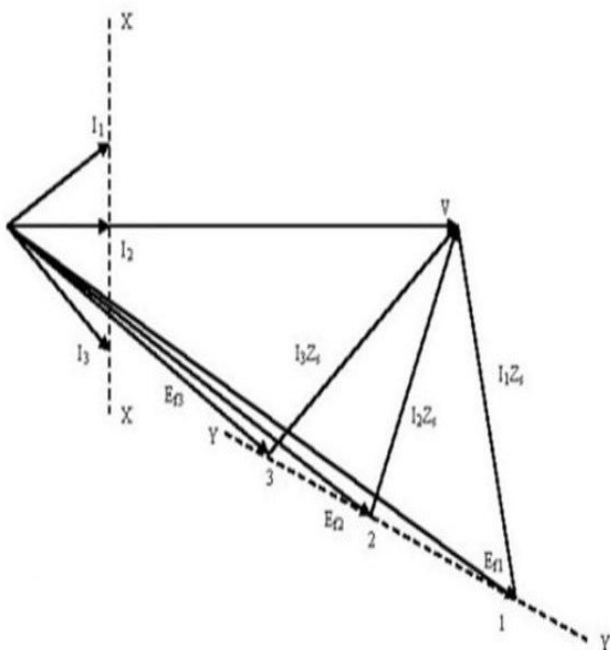


Figure 1. Effect of field excitation on performance of a synchronous motor XX – locus of armature current at constant power; YY – locus of open-circuit voltage at constant power.

When the synchronous motor operates with constant power input, the variation of armature current with field current is thus a V-shaped curve. In general, over-excitation will cause the synchronous motor to operate at a leading power factor, while under-excitation will cause the motor to operate at a lagging power factor. The synchronous thus possesses variable power factor characteristic [6].

The equation of the cylindrical rotor motor becomes:

$$V_a = E_a + (R_a + jX_s)I_a \quad \dots (3)$$

Figure 2 illustrates the relation between E_a and supply voltage V_a for three types of loads [7]:

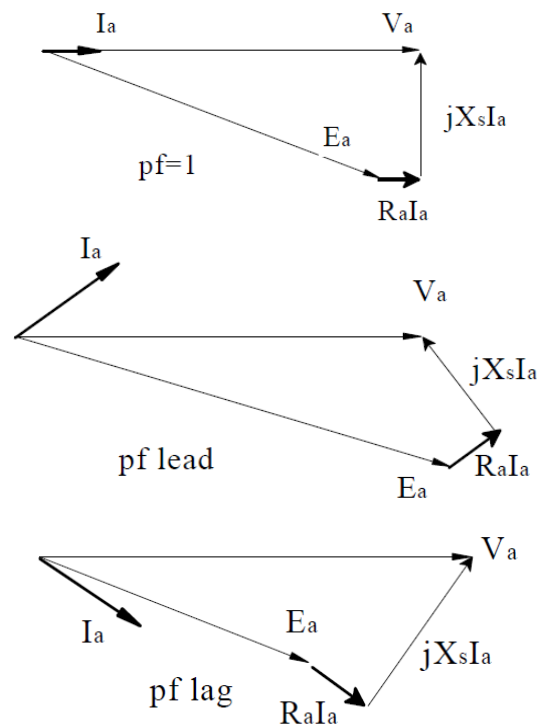


Figure 2. Different vector diagrams of synchronous motor

The relation between the stator current and the field current of a synchronous motor at a constant terminal voltage and with a constant shaft load is known to be a V-curve.

V-Curve Analysis

The analysis of the V-curves for a given power delivered, the excitation will control the power factor. Hence the synchronous motor can be set to operate at any desired power factor [8].

Usually powers factor it to be at unity since it giving the less current magnitude, hence less Joules losses.

A special application of synchronous motor running at no-load by varying the excitation to control a leading/lagging power factor; hence this becomes either “Capacitor”, a “Small Resistor”, or a “Reactor”. This can be controlled continuously with the excitation current and called “SYNCHRONOUS COMPENSATOR” that can compensate for reactive power [9].

Figure 3 shows the equivalent circuit of the synchronous motor.

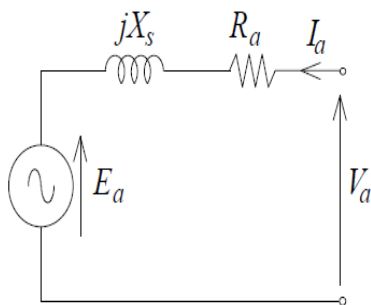


Figure 3. the equivalent circuit of the synchronous motor

When the rotor field current is just enough to produce the required magnetic flux, a unit power factor is obtained. If the rotor field current is more than required the spurious reactive power is to be exported to the power lines of the power supply. This state is known as over excitation [10].

In practice, because of this feature, synchronous motors are often run at no active load as synchronous condensers for the purpose of power factor correction. Figure 4 explain the phasor diagram of the power factor compensation for an inductive load, which is common for factories using large induction motor drives, and a synchronous condenser. By controlling the rotor excitation current such that the synchronous condenser draws a line current of leading phase angle, whose imaginary component cancels that of the load current, the total line current would have a

minimum imaginary component. Therefore, the overall power factor of the inductive load and the synchronous condenser would be close to one and the magnitude of the overall line current would be the minimum[9,10].

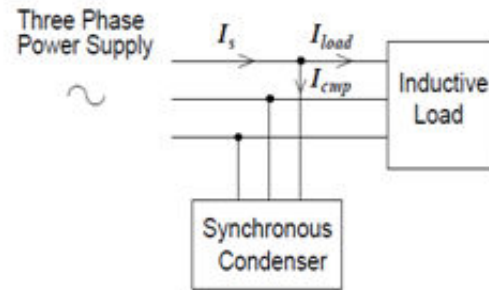


Figure 4. Power factor compensation for an inductive load using synchronous condenser

Synchronous motor is motor in which power factor can be controlled by adjusting the excitation of the rotating DC field. Unlike AC induction motors which always run at a lagging power factor, synchronous motors can run at unity or even at a leading power factor. This will improve the over-all electrical system power factor and voltage drop and also improve the voltage drop at the terminals of the motor [10].

Simulation setup

- Considering the MATLAB m-file for synchronous motor 2400V,10000kVA the results of table1 and V-curves of table 1 are obtained.

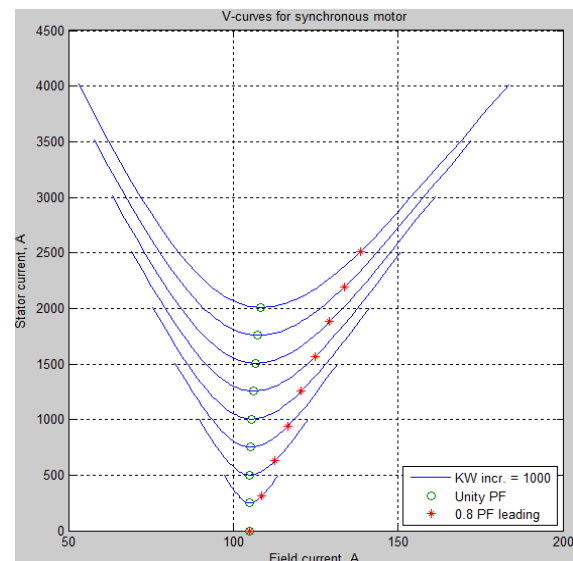


Figure 5. The V-curves of 2400V,10000kVA synchronous motor

| Field current (A) | Stator current (A) |
|-------------------|--------------------|
| 56.86170118 | 3849.001795 |
| 66.12020126 | 3363.826002 |
| 76.81813297 | 2862.558901 |
| 85.26629634 | 2527.429394 |
| 92.31076748 | 2296.299024 |
| 98.31128871 | 2136.034846 |
| 104.3535896 | 2027.805957 |
| 108.1848908 | 1978.932407 |
| 113.6792447 | 1935.540772 |
| 115.4722994 | 1928.463132 |
| 117.2573121 | 1924.940475 |
| 119.0407526 | 1924.940475 |
| 120.838052 | 1928.463132 |
| 122.7193351 | 1935.540772 |
| 124.6195884 | 1946.238776 |
| 126.5460936 | 1960.657066 |
| 128.5065309 | 1978.932407 |
| 134.6770262 | 2058.896498 |
| 141.4986611 | 2182.948355 |
| 150.1256311 | 2364.216616 |
| 160.816443 | 2625.327035 |
| 164.9570039 | 2736.313956 |
| 169.5323148 | 2862.558901 |
| 182.4181286 | 3172.394313 |
| 190.0056376 | 3363.826002 |
| 198.5915235 | 3586.817106 |
| 208.4239637 | 3849.001795 |

Table 1. The V-Curve resultant table of 2400V,10000kVA synchronous motor

After the simulation of the 2400V,10000kVA synchronous motor using MATLAB m-file, the following results and comments is presented:

- As load on the motor increases, the armature (stator) current I_a increases regardless of excitation.
- For under and over excited motor, the power factor (p.f.) tends to approach unity with increase in load.
- Both with under and over excitation, change in p.f. is greater than in I_a with increase in load.
- With normal excitation, when load is increased, change in I_a is greater than in

p.f. which tends to become increasingly lagging.

- The magnitude of armature current varies with excitation. The current has large value both for low and high values of excitation (though it is lagging for low excitation and leading for higher excitation). In between, it has minimum value corresponding to a certain excitation.

For the same input, the armature current varies over a wide range and so causes the power factor also to vary accordingly. When over-excited, motor runs with leading power factor and with lagging power factor when under-excited. In between, the power factor is unity. The curve for power factor looks like inverted V curve. Also, the minimum armature current corresponds to unity power factor.

- As per the first point, an over-excited motor can be run with leading power factor. This property renders it extremely useful for phase advancing (and so power factor correction) purposes in the case of industrial loads driven by induction motors and lighting and heating rods supplied through transformers.
- Both transformers and induction motors draw lagging currents from the line. Especially on light loads, the power drawn by them has a large reactive component and the power factor has a very low value. This reactive component, though essential for operating the electrical machinery, entails appreciable losses in many ways. By using synchronous motors in conjunction with induction motors and transformers, the lagging reactive power required by the latter is supplied locally by the leading reactive component taken by the former, thereby relieving the line and generators of much of the reactive component. Hence, they now supply only the active component of the load current. The complete details of m-file developed for synchronous motor 2400V,10000kVA produce the V-curves for this study are illustrated in the appendix.
- Synchronous motors are more expensive than the lower horsepower motors that currently applicable in industrial environment.

Conclusion

Synchronous motors have the unique ability to run at different power factors.

Motors actually require electric power for two reasons. The first is to supply power current that gets converted to mechanical power for the load and rotational losses. The second is the excitation current. Excitation current stores energy in the magnetic field and releases it back to the source. Excitation current, which does no actual work, is ninety degrees out of phase with power current.

In this paper the V-curves of the 2400V,10000kVA synchronous motor are studied using MATLAB M-file.

The simulation results gives the following points are concluded:

- Precise speed regulation makes the synchronous motor an ideal choice for certain industrial processes and as a prime mover for generators.
- Synchronous motors have speed / torque characteristics which are ideally suited for direct drive of large horse-power, low-rpm loads such as reciprocating compressors.
- Synchronous motors operate at an improved power factor, thereby improving overall system power factor and eliminating or reducing utility power factor penalties. An improved power factor also reduces the system volt-age drop and the voltage drop at the motor terminals.
- So, the V-Curve analysis and study of synchronous motor using MTLAB m-file is a good choice in industrial environments.

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Appendix

The simulated MTLAB M-file used for the study:

```

VL=2400; KVA=10000; PF=0.8;
PR=KVA*PF; % Rated values
Xsu=VL^2/(KVA*1000); Xl=0.1*Xsu;
Ra=1e-5*VL^2/KVA;
Voc=[0 1700 1950 2200 2300 2400 2500
2600 2700 2800 2900 ...
3000 3100 3300]';
Ifoc=[ 0 70 83 98 105 115 126 140 160 180
205 235 280 400]';
IaR=1000*KVA/VL/sqrt(3)*(PF+j*sin(acos
(PF)));
Er=abs(VL/sqrt(3)-j*IaR*Xl-IaR*Ra);
Ifs=interp1(Voc/sqrt(3),Ifoc,Er);
Ifg=Ifoc(2)/(Voc(2)/sqrt(3))*Er;
Xss=(Xsu-Xl)*Ifg/Ifs+Xl;
Ef=abs(VL/sqrt(3)-j*IaR*Xss-IaR*Ra);
IfR=interp1(Voc/sqrt(3),Ifoc,Er)*Ef/Er;
axis([0, IfR, 0, abs(IaR)]);
ncurv=9; Po=linspace(0, PR, ncurv)*1000;
ang=linspace(-60, 60, 50)*pi/180;
n=length(ang);
for i=1:ncurv
    for k=1:n
        Ia(k)=Po(i)/sqrt(3)/VL/cos(ang(k));
        I=Ia(k)*cos(ang(k))+j*Ia(k)*sin(ang(k));
        Er=abs(VL/sqrt(3)-j*I*Xl-I*Ra);
        Ifs=interp1(Voc/sqrt(3),Ifoc,Er);
        Ifg=Ifoc(2)/Voc(2)/sqrt(3)*Er;
        Xss=(Xsu-Xl)*Ifg/Ifs+Xl;
        Ef=abs(VL/sqrt(3)-j*I*Xss-I*Ra);

        If(k)=interp1(Voc/sqrt(3),Ifoc,Er)*Ef/Er;
    end
    Iau=Po(i)/sqrt(3)/VL; Er=abs(VL/sqrt(3)-
j*Iau*Xl-Iau*Ra);
    Ifs=interp1(Voc/sqrt(3),Ifoc,Er);
    Ifg=Ifoc(2)/Voc(2)/sqrt(3)*Er;
    Xss=(Xsu-Xl)*Ifg/Ifs+Xl;
    Ef=abs(VL/sqrt(3)-j*Iau*Xss-Iau*Ra);
    Ifu=interp1(Voc/sqrt(3),Ifoc,Er)*Ef/Er;
    Ial=Po(i)/sqrt(3)*VL*0.8;
    I=Ial*(0.8+j*0.6);
    Er=abs(VL/sqrt(3)-j*I*Xl-I*Ra);
    Ifs=interp1(Voc/sqrt(3),Ifoc,Er);
    Ifg=Ifoc(2)/Voc(2)/sqrt(3)*Er;
    Xss=(Xsu-Xl)*Ifg/Ifs+Xl;
    Ef=abs(VL/sqrt(3)-j*I*Xss-I*Ra);
    Ifl=interp1(Voc/sqrt(3),Ifoc,Er)*Ef/Er;
    plot(If,Ia,Ifu,Iau,'o',Ifl,Ial,'*'); grid; hold on;

```

```

end
title('V-curves for synchronous
motor');
xlabel('Field current, A'); ylabel('Stator
current, A');

```