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A Survey on Electrical Machines for Variable Speed Applications

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Abstract

This paper presents a survey of system studies on electrical machines for variable speed applications. All electrical machines in general are classified based on their unique characteristic features as inductive - interactive type and variable reluctance type machines. In this paper three electrical machines with three different characteristic features are studied and a choice is made as to which machine is best suited for a variable speed application. The subject of System Theory is applied to study the structure of the three machines. Wind energy generation being a typical variable speed application is chosen as the specific application for which the machine is designed. The three machines taken up for study are Induction Machine and Synchronous Machine for inductive - Interactive type and Switched Reluctance Machine for variable reluctance type. Optimization of power generation and increasing the energy efficiency from wind energy by proper choice and design of a machine is the objective of the study.

Keywords: Induction Machines, Switched Reluctance Machines (SRM), Synchronous Machines, Torque Production, Variable Speed Application, Wind Turbine Generator

1. Introduction

Electrical machines even though being discovered hundreds of years back stills seems to fascinate us because the exact working of it is still an enigma unlike Mechanical machines where we can physically see its working process. Electrical machines can be broadly classified based on two different attributes; one is based on the torque producing mechanism and second based on its magnetic interactions. Based on the torque producing mechanism machines are classified into two types, one is alignment torque producing machines such DC machines, induction and synchronous machines and the second is the reluctance torque producing machine eg. Switched reluctance machines. Based on the magnetic interactions machines are classified as inductive-interactive type machines eg. Induction machines, Synchronous machines, DC machines and variable reluctance type machines eg. Switched Reluctance machines. In this paper the characteristic features of these machines are studied and a suitable machine is chosen for a variable speed application. Wind energy generation being a typical variable speed application is chosen as the specific application for which the machine is designed. Optimization of power generation and increasing the energy efficiency from wind energy by proper choice and design of a machine is the objective of the study.

2. Induction Machines

Induction machines are singly excited systems which consist of a fixed core called the stator carrying a three phase winding in the slots. The moving part is the rotor which has a cage or slip ring winding in the slots. The stator winding is connected to a three phase supply and a uniform rotating magnetic field is produced. The energy transfer from stator to rotor is through induction principle and there is no separate excitation for rotor. This machine has two types of rotor construction one is the squirrel cage type and the second is the slip ring type. The induced e.m.f in the machine is given by,

$$e = 4.44\, f\, \Phi\, T \quad Volts$$

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2.1 Torque Production Mechanism in Induction Machines

The rotating magnetic field produced by the stator links the rotor conductors and induces an e.m.f's in the rotor and the currents produces in rotor interacts with the rotating field to develop the torque. The nature of the torque produced in this machine is called the Alignment torque. The rotor magnetic field and the stator magnetic field rotate at a speed Ns with respect to the stator and hence they are stationary with respect to each other and therefore a steady torque is developed. The torque equation of a three phase induction motor is given by,

$$T = \frac{K\, s\, E_{20}^{\ 2}\, R_2}{R_2^{\ 2} + s^2 X_{20}^{\ 2}}$$

From the expression of torque it is seen that the machine torque is proportional to the square of voltage, depends on slip and the rotor resistance. It may be seen that the rotor will rotate in the same direction as the stator rotating magnetic field. The torque angle and hence the torque produced are maximum when the rotor is a purely resistive circuit. To achieve higher torque at starting, therefore in a slip ring rotor extra resistance is connected in the rotor circuit so that the rotor becomes more resistive and torque angle is increased. The speed of the rotor will, however be less than that of synchronous speed. The speed of the rotor relative to that of the stator rotating field is called slip. If the load on the rotor shaft is increased the slip increases. ie the rotor speed decreases. The induced emf in the rotor increases hence the rotor current increases. The rotor develops more torque to balance the increased load torque requirement. The relationship between synchronous speed, rotor speed and slip is given by,

$$s = \frac{Ns - Nr}{Ns}$$

$$Nr = Ns(1 - S)$$

$$Nr = \frac{120\, f\,(1 - S)}{P}$$

The above equation shows that the speed of an induction machine depends on slip 's' of the machine, frequency of the stator supply 'f' and number of poles for which the windings are made. The slip of an induction machine for a particular load can be changed by changing the rotor circuit resistance. In squirrel cage motors rotor circuit resistance cannot be varied, so the speed cannot be controlled with slip in squirrel cage motors[1]. The speed control of induction motor by varying rotor circuit resistance has major disadvantages like decreased system efficiency due to power lost in the rotor circuit. The speed variation by changing the supply stator voltage is the next strategy, but if the voltage is reduced then the torque is reduced which in turn reduces speed. This method of speed control requires voltage changing power electronics equipments, so the cost is a major disadvantage. Next the speed of an induction motor is directly proportional to supply frequency. There are, however several drawbacks in this system. Electricity supply authorities supply power at a fixed frequency of 50 Hz. Frequency conversion equipments are to be installed by the industry at additional cost. Also if the frequency is changed the supply voltage should also simultaneously be changed. This is because if the supply frequency is reduced keeping the applied voltage constant, the flux increases. If the flux is increased, higher core loss will reduce the efficiency. On the other hand if the frequency is increased, flux will decrease thereby reducing the torque developed. Lastly speed variation by changing the number of poles is a tedious process in construction of the machine also the speed variation is of limited range. Also running the induction machine as a generator is limited because induction generator will only generate when it is connected to the supply lines and does not supply power to any resistive load. From the above discussion we can see that the stator and rotor parameters are coupled unlike DC machines where armature and field are decoupled, makes the induction machine not suitable for a variable speed application.

3. Synchronous Machines

Synchronous machines are doubly excited systems i.e. in stator we have a three phase AC excitation and in the rotor we have a DC excitation. Magnetic locking happens between the stator and the rotor magnetic fields so that there is no slip in this machine. It's a fixed speed machine which runs at the synchronous speed only. Synchronous machines are classified into two types based on their rotor construction one is the salient pole type and the other is the non-salient pole or cylindrical type. A synchronous machine works as a generator when its rotor carrying the field system is rotated by a prime mover. The flux lines are cut by the conductors in the stator and an emf is induced according to the Faraday's law of electromagnetic induction. The emf equation of the machine is given by,

$e = 4.44\, f\, \Phi\, T \qquad Volts$

When the machine is operating in the generating mode the machine supplies a lagging power factor current when over excited and supplies a leading power factor current when under excited.

3.1 Torque Production Mechanism in Synchronous Machines

The machine will work as a motor when a three phase voltage is applied across the stator windings. The AC excitation in the stator and the DC excitation in the rotor produces two different magnetic fields along their respective axes. The torque is produced in this machine when the two fields tends to align themselves[2]. So the nature of the torque produced in this machine is Alignment torque. For a fixed excitation and constant terminal voltage the torque equation of the machine is given by,

$T=K \sin \delta$

Where K is a constant and δ is known as the torque angle or power angle. The electromagnetic torque developed is a sine function of angle δ. The motor operates at fixed torque angle for a given mechanical load torque and runs at synchronous speed only. If the load torque is increased the rotor decelerates for a short while before that the torque angle is increased to a new value and the machine settles to an new torque angle but the speed is still the synchronous speed. The maximum torque developed by this machine is at $\delta = 9^{\circ}$ and is called the pull out torque. In this machine is loaded beyond this torque angle the machine falls out of synchronism. And in the motoring mode the machine draws a leading power factor current when over excited and draws a lagging power factor current when under excited[3]. Another special feature of the synchronous motor is that at no load the machine behaves as a variable capacitor or inductor by simply varying its excitation. The machine operated at such a condition is known as a synchronous condenser and finds application in power system network for improving the power factor under heavy load conditions and decreasing the power factor under light load conditions, and thereby controlling the voltage profile of the power system. In synchronous machine has a synchronous locking between the stator and rotor fields also speed is synchronous independent of load which make this machine suitable only for fixed speed applications[4].

4. Switched Reluctance Machine

Switched Reluctance Machine (SRM) is a special type of machine which differs drastically in its characteristic features compared to the conventional machines such as induction, synchronous and DC machines[5]. There is a fundamental difference in the torque producing mechanism of SRM, here the torque produced is called as the Reluctance torque whereas in conventional machines the torque produced is called as the Alignment torque. SRM is a singly excited system with only stator being given excitation, when a phase is excited in the stator it attracts the nearest rotor pole towards it there by reducing the reluctance path between them. Here in SRM there is only one magnetic field unlike conventional machines where there are two magnetic fields one for stator and another for rotor. The switched reluctance machine is a doubly salient pole machine with both stator and rotor has salient poles. The construction of SRM is very simple as there are no windings or permanent magnets on the rotor which reduces the cost of the machine[6]. The stator and rotor are made of stacked iron laminations with copper windings on the stator alone. To excite the machine the power electronic converter energizes the appropriate phase based on the position of the rotor, an information obtained from the rotor position sensor. The voltage equation on one of the phase is given by,

$$V = R_s.i + \frac{d\{L(\theta,i)i\}}{dt}$$

$$V = R_s.i + L(\theta,i).\frac{di}{dt} + \frac{dL(\theta,i)i}{d\theta}\omega.i$$

In SRM the inductance L depends on both rotor position (θ) as well as phase current "i" unlike conventional machines where the rotor position information is not important[7]. The induced emf of SRM is given as

$$e = \frac{dL(\theta,i)}{d\theta}.\omega.i$$

$$e = K_b.\omega.i$$

4.1 Torque Production Mechanism in Switched Reluctance Machines

The torque production in the switched reluctance machine is based on the principle of variation of the reluctance between the stator and rotor. The rotor is aligned with the nearest stator pole by sequentially switching the currents into the stator winding, the rotor is rotated. In any magnetic circuit, the rotating member prefers to come to the minimum reluctance position at the instance of excitation[8]. This variable reluctance based torque production in SRM is fundamentally a very unique phenomenon unlike conventional machines where the torque production is by interaction and alignment of two magnetic fields. The torque equation of the switched reluctance motor is given by,

$$T = \frac{1}{2}.i^2.\frac{dL}{d\theta}$$

where i is the phase current; L is the phase inductance; θ is the rotor angular position From the above torque expression we can see that the torque is proportional to the square of the current can be unipolar to produce unidirectional torque[9]. Note that this is quite contrary to the case of conventional machines. Here only one power switch is required for the control of current in the phase winding, this reduces the number of power switches in the converter. Also the torque equation is very similar to a DC series motor, hence SRM will have a good starting torque. Unlike conventional induction and synchronous machines, SRM cannot be operated directly from a three phase supply line. Also the mutual coupling between phases is negligible in SRM which gives complete independence for control and torque generation purpose. All the above features makes SRM a machine inherently suitable for a variable speed application[10].

5. Conclusion

In this paper the characteristic features of conventional electrical machines such as induction, synchronous machines and a special machine the switched reluctance machine is analyzed. A study was done on the torque producing mechanism of these machines so as to find which machine is best suited for a variable speed application. Wind energy generation being a typical variable speed application is chosen as a specific application for which the machines characters were analyzed. As a concluding remark switched reluctance machine seems to be best suited for a variable speed application. However more experiments and research has to be done to validate and prove the above conclusion.

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