EE3014 POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

UNIT II

ELECTRICAL MACHINES FOR WIND ENERGY CONVERSION

2.1 REFERENCE THEORY FUNDAMENTALS-PRINCIPLE OF OPERATION AND ANALYSIS

INTRODUCTION TO ELECTRO-MECHANICAL ENERGY CONVERSION

Energy exists in many forms, and we use numerous devices on a daily basis that convert one form of energy into another. When we speak of electromechanical energy conversion, however, we mean either the conversion of electric energy into mechanical energy or vice versa. For example, an electric motor converts electric energy into mechanical energy. On the other hand, an electric generator transforms mechanical energy to electric energy. Electromechanical energy conversion is a reversible process except for the losses in the system. The term "reversible" implies that the energy can be transferred back and forth between the electrical and the mechanical systems. However, each time we go through an energy conversion process, some of the energy is converted into heat and is lost from the system forever.

When a current-carrying conductor is placed in a magnetic field, it experiences a force that tends to move it. If the conductor is free to move in the direction of the magnetic force, the magnetic field aids in the conversion of electric energy into mechanical energy. This is essentially the principle of operation of all electric motors. On the other hand, if an externally applied force makes the conductor move in a direction opposite to the magnetic force, the mechanical energy is converted into electric energy. Generator action is based upon this principle.

Introduction For energy conversion between electrical and mechanical forms, electromechanical devices are developed. In general, electromechanical energy conversion devices can be divided into three categories:

Transducers (for measurement and control): These devices transform the signals of differentforms. Examples are microphones, pickups, and speakers.

Force producing devices (linear motion devices): These type of devices produce forces mostly for linear motion drives, such as relays, solenoids (linear actuators), and electromagnets.

Continuous energy conversion equipment: These devices operate in rotating mode. A device would be known as a generator if it converts mechanical energy into electrical energy, or as a motor if it does the other way around (from electrical to mechanical). Since the permeability of ferromagnetic materials is much larger than the permittivity of dielectric materials, it is more advantageous to use electromagnetic field as the medium for electromechanical energy conversion.

REFERENCE THEORY FUNDAMENTALS

Transformation of three phase electrical quantities to two phase quantities is a usualpractice to simplify analysis of three phase electrical circuits. Polyphase A.C machines can berepresented by an equivalent two phase model provided the rotating polyphases winding in rotorand the stationary polyphase windings in stator can be expressed in a fictitious two axes coils.The process of replacing one set of variables to another related set of variable is called windingtransformation or simply transformation or linear transformation. The term linear transformationmeans that the transformation from old to new set of variable and vice versa is governed bylinear equations. Theequations relating old variables and new variables are called transformation equation and the following general form:

[New Variable] = [Transformation matrix][Old variable] [Old Variable] = [Transformation matrix][New variable]

Transformation matrix is a matrix containing the coefficients that relates new and old variables. Note that the second transformation matrix in the above-mentioned general form is inverse of first transformation matrix. The transformation matrix should account for power invariance in the two frames of reference. In case power invariance is not maintained, then torque calculation should be from original machine variables only.

INTRODUCTION TO REFERENCE FRAME THEORY

Overview

As the application of ac machines has continued to increase over this century, new techniques have been developed to aid in their analysis. Much of the analysis has been carried out for the treatment of the well-known induction machine. The significant breakthrough in the analysis of three-phase ac machines was the development of reference frame theory. Using these techniques, it is possible to transform the phase variable machine description to another reference frame. By judicious choice of the reference frame, it proves possible to simplify considerably the complexity of the mathematical machine model. While these techniques were initially developed for the analysis and simulation of ac machines, they are now invaluable tools in the digital control of such machines. As digital control techniques are extended to the control of the currents, torque and flux of such machines, the need for compact, accurate machine models is obvious.

Fortunately, the developed theory of reference frames is equally applicable to the synchronous machines, such as the Permanent Magnet Synchronous Machine (PMSM). This machine is sometimes known as the sinusoidal brushless machines or the brushless ac machine and is very popular as a high-performance servo drive due to its superior torque-to-weight ratio and its high dynamic capability. It is a three-phase synchronous ac machine with permanent- magnet rotor excitation and is designed to have a sinusoidal torque-position characteristic. The aim of this section is to introduce the essential concepts of reference frame theory and to introduce the space vector notation that is used to write compact mathematical descriptions of ac machines. Over the years, many different reference frames have been proposed for the analysis of ac machines. The most commonly used ones are the so-called stationary reference frame and the rotor reference frame.

Clarke's Transformation

The transformation of stationary circuits to a stationary reference frame was developed by E. Clarke. The stationary two-phase variables of Clarke's transformation are denoted as α and β. As shown in Figure 2.1, α-axis and β-axis are orthogonal.

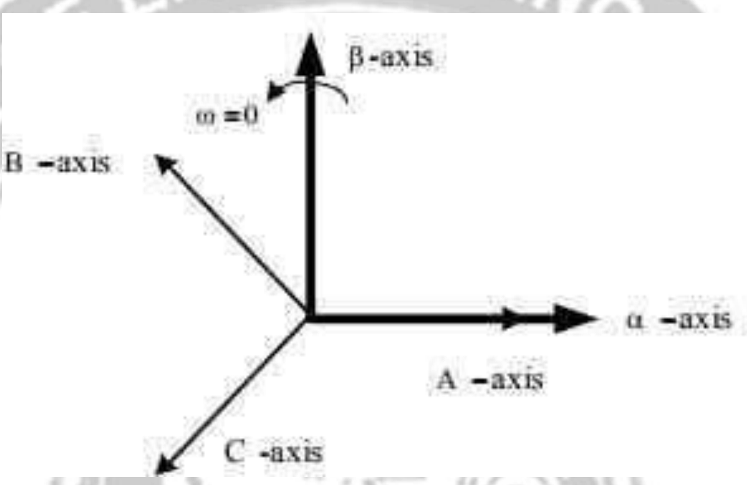


Figure 2.1: Clarke's transformation

In order for the transformation to be invertible, a third variable, known as the zero-sequence component, is added. The resulting transformation is

$$[f_{\propto\beta 0}] = T_{\propto\beta 0}[f_{abc}] \tag{1}$$

where

$[f_{\propto\beta 0}] = [f_{\propto} \quad f_{\beta} \quad f_0]^T$

and

$[f_{abc}] = [f_a \quad f_b \quad f_c]^T$

Where f represents voltage, current, flux linkages, or electric charge and the transformationmatrix, $T_{\propto\beta 0}$ is given by

$$T_{\propto\beta 0} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{2}$$

The inverse transformation is given by

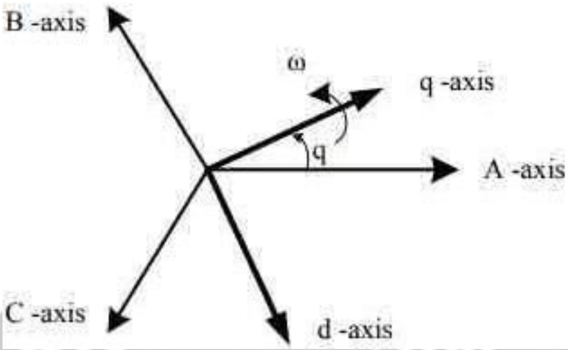
$$[f_{abc}] = T_{\propto\beta0}{}^{-1}[f_{\propto\beta0}] \qquad (3)$$

where the inverse transformation matrix is presented by

$$T_{\propto\beta0}{}^{-1} = \frac{2}{3}\begin{bmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \end{bmatrix} \qquad (4)$$

Park's Transformation

Park's transformation, a revolution in machine analysis, has the unique property of eliminating all time varying inductances from the voltage equations of three-phase ac machines due to the rotor spinning. Although changes of variables are used in the analysis of ac machines to eliminate time-varying inductances, changes of variables are also employed in the analysis of various static and constant parameters in power system components. Fortunately, all known real transformations for these components are also contained in the transformation to the arbitrary reference frame. The same general transformation used for the stator variables of ac machines serves the rotor variables of induction machines. Park's transformation is a well-known three- phase to two-phase transformation in synchronous machine analysis.



Park's transformation

The transformation equation is of the form

$$[f_{dq0s}] = T_{dq0}(\theta)[f_{abcs}] \quad (1)$$

where

$$[f_{dq0s}] = [f_{qs} \quad f_{ds} \quad f_{0s}]^T$$

and

$$[f_{abcs}] = [f_{as} \quad f_{bs} \quad f_{cs}]^T$$

and the dq0 transformation matrix is defined as

$$T_{dq0}(\theta) = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (2)$$

θ is the angular displacement of Park‘s reference frame and can be calculated by

$$\theta = \int_0^t \omega(\zeta)\, d\zeta + \theta(0) \quad (3)$$

where ζ is the dummy variable of integration. It can be shown that for the inverse transformationwe can write

$$[f_{abcs}] = T_{dq0}(\theta)^{-1}.[f_{dq0s}] \quad (4)$$

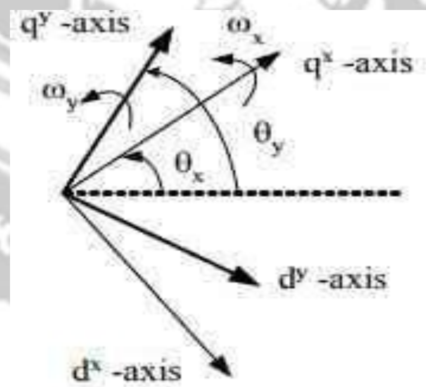
$$T_{dq0}(\theta)^{-1} = \begin{bmatrix} \cos\,\theta & \sin\theta & 1 \\ \cos\,(\theta - \frac{2\pi}{3}) & \sin\,(\theta - \frac{2\pi}{3}) & 1 \\ \cos\,(\theta + \frac{2\pi}{3}) & \sin\,(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \qquad (5)$$

where the inverse of Park's transformation matrix is given by

In the previous equations, the angular displacement θ must be continuous, but the angular velocity associated with the change of variables is unspecified. The frame of reference may rotate at any constant, varying angular velocity, or it may remain stationary. The angular velocity of the transformation can be chosen arbitrarily to best fit the system equation solution or to satisfy the system constraints. The change of variables may be applied to variables of any waveform and time sequence; however, we will find that the transformation given above is particularly appropriate for an a-b-c sequence.

Transformations between Reference Frames

In order to reduce the complexity of some derivations, it is necessary to transform the variables from one reference frame to another one. To establish this transformation between any two reference frames, we can denote y as the new reference frame and x as the old reference frame. Both new and old reference frames are shown in Figure.



Transformation between two reference frames

It is assumed that the reference frame x is rotating with angular velocity ωx and the reference frame y is spinning with the angular velocity ωy. θx and θy are angular displacements of reference frames x and y, respectively. In this regard, we can rewrite the transformation equation as

$$[f_{dq0s}^{y}] = T_{dq0s}^{x \to y} \cdot [f_{dq0s}] \qquad (1)$$

But we have

$$[f_{dq0s}^{x}] = T_{dq0s}^{x} \cdot [f_{abcs}] \qquad (2)$$

If we substitute (2) in (1) we get

$$[f_{dq0s}^{y}] = T_{dq0s}^{x \to y} \cdot T_{dq0s}^{x} \cdot [f_{abcs}] \qquad (3)$$

In another way, we can find out that

$$[f_{dq0s}^{y}] = T_{dq0s}^{y}.[f_{abcs}] \qquad (4)$$

From (3) we obtain

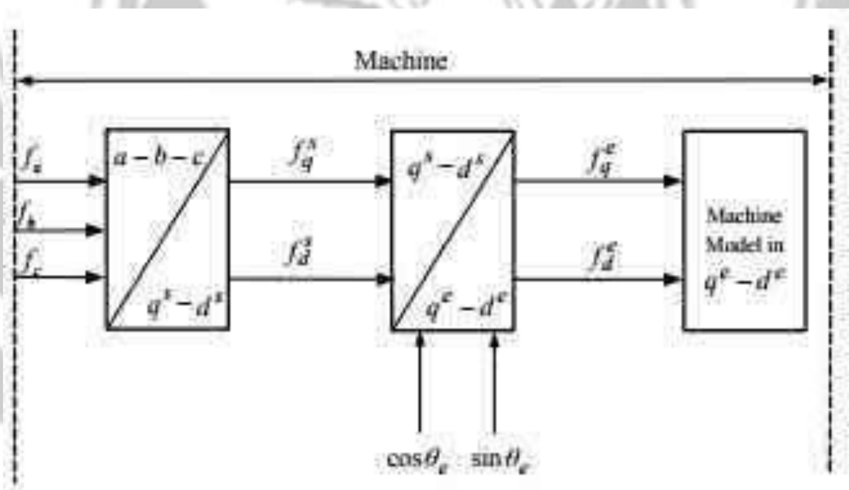
$$T_{dq0s}^{x\to y} = T_{dq0s}^{y}.T_{dq0s}^{x}{}^{-1} \qquad (5)$$

Then, the desired transformation can be expressed by the following matrix:

$$T_{dq0s}^{x\to y} = \begin{bmatrix} \cos(\theta_y - \theta_x) & -\sin(\theta_y - \theta_x) & 0 \\ \sin(\theta_y - \theta_x) & \cos(\theta_y - \theta_x) & 0 \\ 1 & 1 & 1 \end{bmatrix} \qquad (6)$$

Field Oriented Control (FOC) Transformations

Machine side transformation in field oriented control

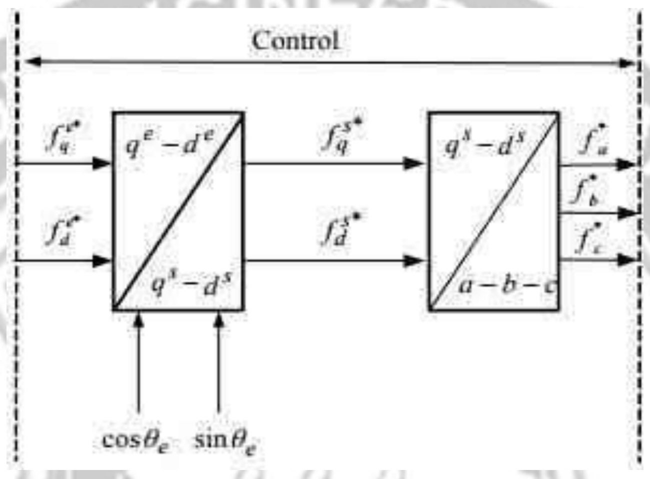


Machine side transformation in field oriented control

In the case of FOC of electric machines, control methods are performed in a two-phase reference frame fixed to the rotor (q^r -d^r) or fixed to the excitation reference frame (q^e -d^e). We want to transform all the variables from the three-phase a-b-c system to the two-phase stationary reference frame and then retransform these variables from the stationary reference frame to a rotary reference frame with arbitrary angular velocity of ω. These transformations are usually cascaded. The block diagram of this procedure is shown in Figure

Variable transformation in the field oriented control.

In this figure, f denotes the currents or voltages and q^e -d^e represents the arbitrary rotating reference frame with angular velocity θ_e and q^s -d^s represents the stationary reference frame. In the vector control method, after applying field oriented control it is necessary to transform variables to stationary a-b-c system. This can be achieved by taking the inverse transformation of variables from the arbitrary rotating reference frame to the stationary reference frame and then to the a-b-c system. In this block diagram, * is a representation of commanded or desired values of variables.



Variable transformation in the field oriented control

Commonly used reference frames

Based on speed of reference frame there are four major type of reference frames

1. **Arbitrary reference frame:** Reference frame speed is unspecified (**ω**), variables denoted by $\mathbf{f_{dqos}}$ or $\mathbf{f_{ds}}$, $\mathbf{f_{qs}}$ and $\mathbf{f_{os}}$, transformation matrix denoted by $\mathbf{K_s}$.

2. **Stationary reference frame:** Reference frame speed is zero (**ω=0**), variables denoted by $\mathbf{f^s_{dqo}}$ or $\mathbf{f_d^s}$, $\mathbf{f_q^s}$ and $\mathbf{f_{os}}$, transformation matrix denoted by $\mathbf{K_s^s}$.

3. **Rotor reference frame:** Reference frame speed is equal to rotor speed (**ω= ωr**), variables denoted by $\mathbf{f^r_{dqo}}$ or $\mathbf{f_d^r}$, $\mathbf{f_q^r}$ and $\mathbf{f_{os}}$, transformation matrix denoted by $\mathbf{K_s^r}$.

4. **Synchronous reference frame:** Reference frame speed is equal to synchronous speed (**ω= ωe**), variables denoted by $f^e_{\mathbf{dqo}}$ or $\mathbf{f_d^e}$, $\mathbf{f_q^e}$ and $\mathbf{f_{os}}$, transformation matrix denoted by $\mathbf{K_s^e}$.

The choice of reference frame is not restricted but otherwise deeply influenced by the type of analysis that is to be performed so as to expedite the solution of the system equations or to satisfy system constraints. The best suited choice of reference frame for simulation of induction machine for various cases of analysis is listed here under:

- **Stationary reference frame** is best suited for studying stator variables only, for example variable speed stator fed IM drives, because stator d-axis variables are exactly identical to stator phase a-variable.

- **Rotor reference frame** is best suited when analysis is restricted to rotor variables as rotor d-axis variable is identical to phase-a rotor variable.

- **Synchronously rotating reference frame** is suitable when analog computer is employed because both stator and rotor d-q quantities becomes steady DC quantities. It isalso best suited for studying multi-machine system.

It is worthwhile to note that all three types of reference frame can be obtained from arbitrary reference frame by simply changing ω. Modeling in arbitrary reference frame is therefore beneficial when a wide range of analysis is to be done.

Induction Machine Model in the Park Reference Frame

The induction machine was modeled using two separate frames. The first one is used to express stator quantities; the second one is used to express rotor quantities. Since these two frames are linked with angle θ, a model of the machine in a common frame named d, q can be obtained using the two rotation matrices. At a certain point, the position of the magnetic field $\vec{o}$

rotating in the air gap is pinpointed by angle θ_s; in relation to stationary axis $_{sa}$: For the development of the machine model, a Park reference frame is assumed to be lined up with this $\vec{o}$

magnetic field and to rotate at the same speed (ω_s): Angle θ_s corresponds to the angle of axes $_{sx}$

and θ_r; angle θ_r corresponds to the angle of $\vec{o}$ axes $\vec{o}_{rx}$ and $_d$: Transforming angle θ_s is necessary to bring the stator quantities back to the Park rotating reference frame. Transforming angle θ_r is necessary to bring the rotor quantities back. The figure indicates that the angles are linked by a $\vec{o}$

relation in order to express the rotor and stator quantities in the same Park reference frame (;

$\vec{O}_d$; $\vec{O}_q$). This relation is:

$$\theta_s = \theta + \theta_r \qquad (1)$$

The same situation happens between the frame speeds in each frame and the mechanical speed, that is:

$$\omega_s = \omega + \omega_r \qquad (2)$$

$$\omega_s = \frac{d\theta_s}{dt}, = \omega_r = \frac{d\theta_r}{dt}, \omega = p\Omega = \frac{d\theta}{dt} \tag{3}$$

where Ω is mechanical speed and ω is very speed viewed in the electrical space.

The speed of the rotor quantities is ω_r in relation to rotor speed ω. In relation to the stator frame, the rotor quantities consequently rotate at the same speed xs as the stator quantities. Using the Park transform will allow the conception of an induction machine model independent

from the rotor position. Two transformations are used. One [P(θ_s)]is applied to the stator quantities; the other [P(θ_r)]is applied to the rotor quantities.

$$[X_{s\_dqo}] = [\mathrm{P}(\theta_s)][X_{s_{abc}}][X_{r_{dqo}}] = [\mathrm{P}(\theta_r)][X_{r_{abc}}] \tag{4}$$

Direct and squared components x_d, x_q represent coordinates x_a, x_b,x_c in an orthogonal frame of reference rotating in the same plane. Term x_o represents the homopolar component, which is orthogonal to the plane constituted by the system x_a, x_b, x_c.