Stability Analysis of a Slip Power Recovery System under Open Loop and Field Orientation Control

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Abstract- Slip power recovery configuration provides an attractive alternative for variable speed drives and generating systems, due to its high-efficiency and low converter rating. The core component is the doubly-excited machine. Firstly, we present a stability analysis of the doubly-excited machine with open loop voltage and open loop current control in the rotor circuit. Possibilities of open loop control are analyzed. Secondly, we present a unified model of a high-performance slip power recovery system composing of a field-orientation controlled doubly-excited machine, power converters and a dc bus in the rotor circuit. Stability of this composite system represented by the model is studied. Of special interest is when the system functions as a variable-speed motor or as a variable-speed constant-frequency generating system.

I. Introduction

Slip power recovery system composed of a doubly-excited machine and power electronic converters in its rotor circuit is very attractive for variable-speed constant-frequency power generations. It has found increasingly uses in wind power, hydro power, aerospace and naval power generations. It is also an attractive alternative for variable speed drives, competing with more common high performance systems with their machine stators excited by power converters. The advantages of slip power recovery systems include higher efficiency and lower converter rating.

Several variations of the slip power recovery system (SPRS) have been proposed and studied. A wound-rotor induction machine is the most common electric machine used in a SPRS, while the newly proposed choice is the doubly-excited brushless reluctance machine, which provides even higher efficiency and lower maintenance cost [1]. Several types of power electronic converters have been seen in the SPRS, including more common cycloconverters and load or line commutated inverters, and more advanced pulse-width-modulated (PWM) converters, which are becoming the choice for the future when high performance of the drive or generating system is required [2].

Doubly-excited machines used to be known as inherently unstable, and classical controllers had been designed, intended to achieve closed-loop stability over limited speed ranges [3,4]. However, open-loop rotor current control had been shown to be stable [5], also observed by us in the lab experiments. With current regulated in the rotor circuit, there is no rotor damping effect present. Then with rotor damping, open-loop voltage control of doubly-excited wound-rotor machine might also be feasible. The first goal of this paper is then to study the stability of these two types of open loop control.

More advanced control of a SPRS has received attention recently and several schemes have been proposed [1,2,6]. However, many issues regarding high performance operation of slip power recovery systems have not been addressed, especially the complicated interaction of the integrated system components such as the machine, the converter system and the control mechanism.

Field orientation control of the SPRS provides an attractive ladder towards the destination of high performance and high flexibility, exemplified by the variable speed constant frequency wind power generating system proposed in [1]. The system consists of a doubly-excited brushless reluctance machine (DEBRM) and dual PWM inverters with a dc link. In studying control strategy and stability, the DEBRM can be replaced by a more common wound-rotor induction machine, since their dynamic models are similar. The second goal of this paper is then to provide a unified model for the analysis of such a composite system with associated vector control scheme and to study the stability of the system, as a motor or as a generator.

0-7803-1462-x/93$03.00

II. Open Loop Rotor Control

In arbitrary d-q reference frame, the machine dynamical equations can be written as [7]

$$\frac{d\lambda_{ds}}{dt} = v_{ds} - r_s i_{ds} + \omega\lambda_{qs} \quad (1)$$

$$\frac{d\lambda_{qs}}{dt} = v_{qs} - r_s i_{qs} - \omega\lambda_{ds} \quad (2)$$

$$\frac{d\lambda_{dr}}{dt} = v_{dr} - r_r i_{dr} + (\omega - \omega_r)\lambda_{qr} \quad (3)$$

$$\frac{d\lambda_{qr}}{dt} = v_{qr} - r_r i_{qr} - (\omega - \omega_r)\lambda_{dr} \quad (4)$$

$$\frac{d\omega_r}{dt} = \frac{1}{2H}(T_e - T_L - B_m\omega_r) \quad (5)$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr} \quad (6)$$

$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \quad (7)$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds} \quad (8)$$

$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \quad (9)$$

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_s}(\lambda_{qs} i_{dr} - \lambda_{ds} i_{qr}) \quad (10)$$

where $\lambda, v, i, \omega, T_e, T_L$ denote flux, voltage, current, angular speed, electromagnetic torque and load torque, respectively; subscripts d and q denote d-axis component and q-axis component in arbitrary dq reference frame, respectively; r and L denote resistance and inductance, respectively; subscripts s, r and m denote stator, rotor and mutual quantities, respectively; B_m and P denote rotor friction coefficient and machine pole pair, respectively. Note that motor convention is used.

A. *Open Loop Rotor Voltage Control*

From (1) through (10), small signal linearized model can be written as

$$\delta v_{qs} = (r_s + pL_s)\delta i_{qs} + \omega L_s \delta i_{ds} + pL_m \delta i_{qr} + \omega L_m \delta i_{dr} \quad (11)$$

$$\delta v_{ds} = (r_s + pL_s)\delta i_{ds} - \omega L_s \delta i_{qs} + pL_m \delta i_{dr} - \omega L_m \delta i_{qr} \quad (12)$$

$$\begin{aligned} \delta v_{qr} = {} & (r_r + pL_r)\delta i_{qr} + (\omega - \omega_r)L_r \delta i_{dr} + pL_m \delta i_{qs} \\ & + (\omega - \omega_r)L_m \delta i_{ds} - (L_m i_{ds0} + L_r i_{dr0})\delta\omega_r \quad (13) \end{aligned}$$

$$\begin{aligned} \delta v_{dr} = {} & (r_r + pL_r)\delta i_{dr} - (\omega - \omega_r)L_r \delta i_{qr} + pL_m \delta i_{qs} \\ & - (\omega - \omega_r)L_m \delta i_{qs} + (L_m i_{qs0} + L_r i_{qr0})\delta\omega_r \quad (14) \end{aligned}$$

$$\begin{aligned} \delta T_L = {} & \frac{3}{2}\frac{P}{2} L_m (i_{dr0}\delta i_{qs} - i_{qr0}\delta i_{ds} - i_{ds0}\delta i_{qr} \\ & + i_{qs0}\delta i_{dr}) - 2Hp\delta\omega_r - B_m \delta\omega_r \quad (15) \end{aligned}$$

It can be organized into the standard state equations

$$px = Ax + Bu \quad (16)$$

where the state $x = [\delta i_{qs}\ \delta i_{ds}\ \delta i_{qr}\ \delta i_{dr}\ \delta\omega_r]^T$ and the control input $u = [\delta v_{qs}\ \delta v_{ds}\ \delta v_{qr}\ \delta v_{dr}\ \delta T_L]^T$.

Stability property of the system can be studied by analyzing the eigenvalues of the matrix A, which depend on system operating conditions as reflected by $i_{ds0}, i_{qs0}, i_{dr0}, i_{qr0}$, as well as machine parameters. Analytic, or symbolic, expressions of the eigenvalues would be useful in the study of stability regions and in sensitivity analysis, yet they are difficult to derive. The numerical method is then applied in this paper, for different steady-state operation points for which stability analysis is to be performed. Since the fluxes of the doubly-excited machines are approximately constant, constraint by the stator voltage, the steady-state solutions depend mainly on the torque or speed of operation. Steady-state solution method presented in [1] is used in this paper, by noting that the steady-state quantities can be conveniently solved in the dq reference frame oriented with the stator voltage or with the stator flux.

For a 50hp doubly-excited machine, stability in the whole speed range is studied for a combination of different types of torque: as a motoring torque or a generating torque; having a load torque or a prime-mover torque with square torque-speed relation or with constant torque-speed relation; at high or low (rated) torques. Computed real parts of system eigenvalues are shown in Fig. 1 through 2, as functions of speed.

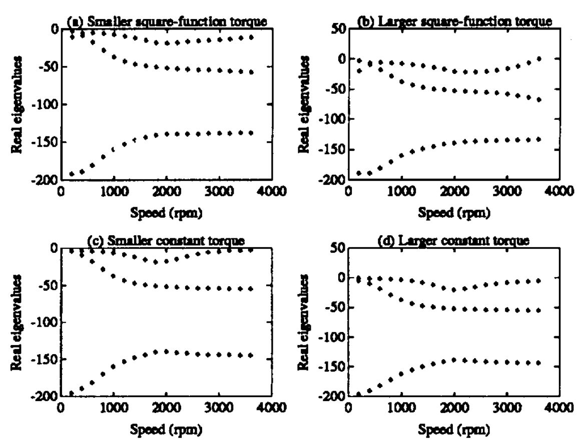

Fig. 1 Real Parts of Eigenvalues with Open Loop Voltage Control (synchronous speed=1800rpm) (as motor)

The system is stable when all the real parts of the eigenvalues of matrix A lie in the left half plane of the complex space. Then the following observations regarding open-loop voltage control can be made:

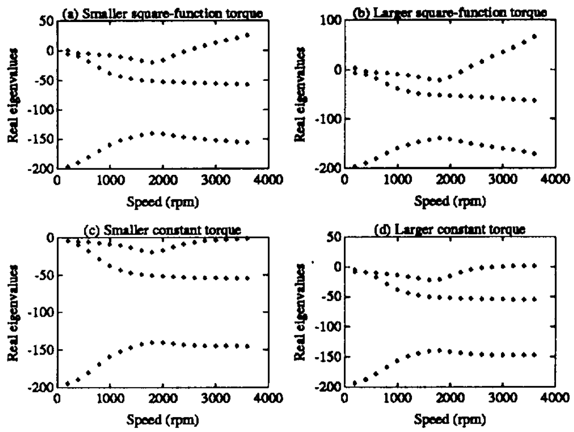

Fig. 2 Real Parts of Eigenvalues with Open Loop Voltage Control (synchronous speed=1800rpm) (as generator)

1. For motor or generator operations, stability property is about the same, though the motor operation possesses better stability;
2. For square function torque and for large constant load torque or prime-mover torque, the system becomes unstable at higher speeds closing to twice the synchronous speed, and a small unstable or marginal stable region exists at low speeds;
3. For smaller or rated constant torques, stable operation is obtained over the entire speed range;
4. The most stable operation points are around the synchronous speed.

B. Open Loop Rotor Current Control

With power converter in the the rotor circuit providing regulated rotor currents, the usual rotor damping effect is missing. However, under certain conditions, stable operation is achievable.

The regulated rotor current can be written as

$$i_{ar} = \sqrt{2} I_r cos(\omega_e t + \gamma) \quad (17)$$

where I_r is the current magnitude and γ is rotor current vector angle with respect to the synchronous frame:

$$\gamma = \int_0^t (\omega_r(\xi) + \omega_s(\xi) - \omega_e(\xi))dt + \gamma_0 \quad (18)$$

where ω_s denotes angular frequency of rotor current with respect to the rotor.

In synchronous d-q reference frame,

$$i_{dr} = -\sqrt{2} I_r sin(\gamma) \quad (19)$$

$$i_{qr} = \sqrt{2} I_r cos(\gamma) \quad (20)$$

Thus

$$pi_{dr} = -\sqrt{2} I_r cos(\gamma) p\gamma - \sqrt{2} sin(\gamma) pI_r \quad (21)$$

$$pi_{qr} = -\sqrt{2} I_r sin(\gamma) p\gamma + \sqrt{2} cos(\gamma) pI_r \quad (22)$$

Assume ideal current regulation with $pI_r = 0$. Then from (1) through (10), with (19) through (22), small signal linearized model can be derived as

$$\delta v_{qs} = (r_s + pL_s)\delta i_{qs} + \omega L_s \delta i_{ds} - \sqrt{2} L_m I_{r0} sin(\gamma_0) p\delta\gamma - \sqrt{2}\omega L_m I_{r0} cos(\gamma_0)\delta\gamma \quad (23)$$

$$\delta v_{ds} = (r_s + pL_s)\delta i_{ds} - \omega L_s \delta i_{qs} - \sqrt{2} L_m I_{r0} cos(\gamma_0) p\delta\gamma + \sqrt{2}\omega L_m I_{r0} sin(\gamma_0)\delta\gamma \quad (24)$$

$$p\delta\gamma = \delta\omega_r + \delta\omega_s \quad (25)$$

$$\delta T_L = \sqrt{2}\frac{3}{2}\frac{P}{2} L_m(-I_{r0} sin(\gamma_0)\delta i_{qs} - I_{r0} cos(\gamma_0)\delta i_{ds} - i_{qs0} I_{r0} cos(\gamma_0)\delta\gamma + i_{ds0} I_{r0} sin(\gamma_0)\delta\gamma) - 2Hp\delta\omega_r - B_m\delta\omega_r \quad (26)$$

Again, it can be organized into the standard state equations (16), with the state $x = [\delta i_{qs}\ \delta i_{ds}\ \delta\gamma\ \delta\omega_r]^T$ and the control input $u = [\delta v_{qs}\ \delta v_{ds}\ \delta\omega_s\ \delta T_L]^T$.

Stability analysis method outlined in the open-loop voltage control case is also applicable. Computation shows that eigenvalues of the matrix A are now affected much more by the initial operating points of γ, than by the loading condition as reflected by the torque or speed. Fig. 3(a) shows the real parts of the eigenvalues as functions of γ_0. It can be seen that approximately for γ_0 in the range of 180° to 360°, the system is maginally stable, while for γ_0 in the range of 0° to 180°, the system is unstable. We have also observed this phenomena in our labs.

With the dynamics involving γ eliminated, i.e. $p\gamma = 0$, the linearized system equations can be written as

$$\delta v_{qs} = (r_s + pL_s)\delta i_{qs} + \omega L_s \delta i_{ds} \quad (27)$$

$$\delta v_{ds} = (r_s + pL_s)\delta i_{ds} - \omega L_s \delta i_{qs} \quad (28)$$

$$\delta T_L = \sqrt{2}\frac{3}{2}\frac{P}{2} L_m(-I_{r0} sin(\gamma_0)\delta i_{qs} - I_{r_0} cos(\gamma_0)\delta i_{ds}) - 2Hp\delta\omega_r - B_m\delta\omega_r \quad (29)$$

The eigenvalues of the system (27) through (29), as shown in Fig. 3(b), are having negative real parts, though close to 0, for all γ_0 from 0° to 360°. The condition $p\gamma = 0$ is equivalent to the following

$$\omega_s + \omega_r = \omega_e \quad (30)$$

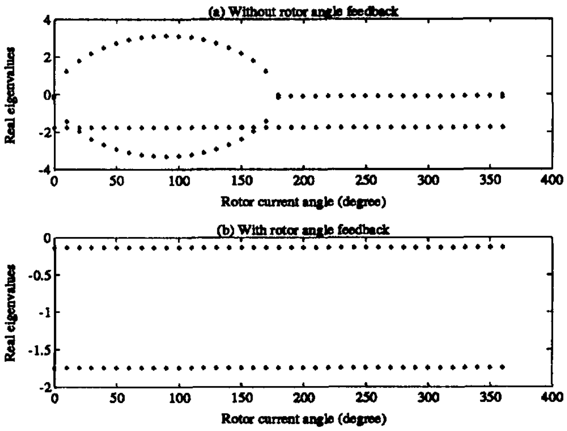

Fig. 3 Real Parts of Eigenvalues with Open Loop Current Control (synchronous speed=1800rpm)

Therefore, for γ_0 from 0° to 360°, open loop current control is stable when the slip frequency of the rotor current is adjusted instantaneously to measure up the difference between the rotor speed and the synchronous speed. In other words, rotor position and speed feedback is necessary.

Steady-state torque of the doubly-excited machine can be derived as

$$T_e \approx -3\frac{P}{2}\frac{1}{\omega_e}V_{as}I_{ar}cos(\gamma) \tag{31}$$

where the stator resistance has been neglected. Therefore, with rotor current regulated, the doubly-excited machine has a torque expression similar to that of a synchronous machine, whose stability depends on the rotor angle, instead of load torque as in the case of a singly-excited induction machine.

In conclusion, for the doubly-excited machine, with the angle of the rotor current vector properly tracked, stable operation can be achieved over the entire range of initial rotor current angle and entire speed range, without the need of additional compensator. However, due to the lack of rotor damping, the system is still close to marginal stable state. These conclusions apply to both motor or generator operations, and almost does not depend on the torque conditions.

III. Stator Field Orientation Control

A schematic slip power recovery system is shown in Fig. 4. Dual PWM converters provide high performance and high flexibility [2]. The rotor side converter realize a stator field orientation control of the machine, which is based on the stator flux d-q model. The reference frame rotates synchronously with respect to the stator flux, with its d-axis overlaps the instantaneous axis of the stator flux. In such a reference frame, it had been shown that the stator active power (or torque) and reactive power can be controlled separately by the two rotor current components i_{qr} and i_{dr} respectively.

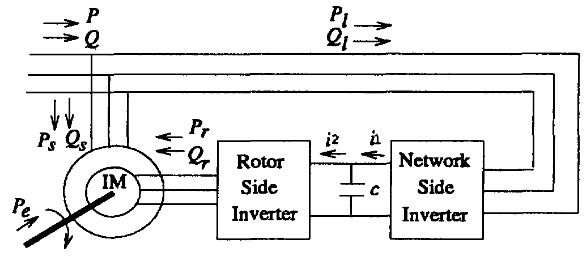

Fig.4 Power Flow of Slip Power Recovery System

A. *Modeling*

Stator field orientation is itself a dynamic process, by continuously adapting the reference frame of the machine model following instantaneous changes in the stator flux reference angle. Therefore, it can be incorporated into the machine dynamics to obtain a unified model, which will become useful and instructive when efforts are made to study the stability of the system under stator field orientation control. In addition, supplemental control will be identified and studied easier. In the following, such a model is developed for the SPRS under stator field orientation control.

In the stator field orientation, the d-axis of the reference frame rotates synchronously, overlapping the instantaneous axis of the stator flux:

$$\begin{pmatrix} \lambda'_{ds} \\ 0 \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} \lambda_{ds} \\ \lambda_{qs} \end{pmatrix} = T \begin{pmatrix} \lambda_{ds} \\ \lambda_{qs} \end{pmatrix} \tag{32}$$

i.e.

$$\theta = tan^{-1}\frac{\lambda_{qs}}{\lambda_{ds}} \tag{33}$$

$$\lambda'_{ds} = \sqrt{\lambda_{ds}^2 + \lambda_{qs}^2} \tag{34}$$

With such a transformation, other variables become

$$\begin{pmatrix} i'_{dr} \\ i'_{qr} \end{pmatrix} = T \begin{pmatrix} i_{dr} \\ i_{qr} \end{pmatrix} \tag{35}$$

$$\begin{pmatrix} v'_{dr} \\ v'_{qr} \end{pmatrix} = T \begin{pmatrix} v_{dr} \\ v_{qr} \end{pmatrix} \tag{36}$$

$$\begin{pmatrix} \lambda'_{dr} \\ \lambda'_{qr} \end{pmatrix} = T \begin{pmatrix} \lambda_{dr} \\ \lambda_{qr} \end{pmatrix} \tag{37}$$

By applying inverse transformation, noting that

$$T^{-1} = \begin{pmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{pmatrix} \tag{38}$$

and by diminishing algebraic terms (6) through (10), the unified machine model becomes (with prime signs left out)

$$p\lambda_{ds} = -\frac{r_s}{L_s}\lambda_{ds} + \frac{r_s L_m}{L_s} i_{dr} + v_{ds} \tag{39}$$

$$p\theta = \frac{r_s L_m}{2L_s}\frac{i_{qr}}{\lambda_{ds}} + \frac{v_{qs}}{2\lambda_{ds}} \tag{40}$$

$$p\omega_r = -\frac{1}{2H}\frac{3}{2}\frac{P}{2}\frac{L_m}{L_s}\lambda_{ds} i_{qr} - \frac{T_L}{2H} - \frac{B_m}{2H}\omega_r \tag{41}$$

$$p\lambda_{dr} = v_{dr} - r_r i_{dr} + (\omega - \omega_r)(L_r - \frac{L_m^2}{L_s}) i_{qr} \tag{42}$$

$$p\lambda_{qr} = v_{qr} - r_r i_{qr} - (\omega - \omega_r)\frac{L_m}{L_s}\lambda_{ds} - (\omega - \omega_r)(L_r - \frac{L_m^2}{L_s}) i_{dr} \tag{43}$$

where $v_{ds} = -\sqrt{2} v_m sin\theta, v_{qs} = \sqrt{2} v_m cos\theta$.

For the converters, a simplified model that ignores harmonics can be applied, which yields

$$i_2 = \frac{3}{\pi} i_{qr} \tag{44}$$

$$i_1 = \frac{3}{\pi} i_{ql} \tag{45}$$

From (44) and (45), the dc bus dynamics can be written as

$$c\frac{dV_d}{dt} = \frac{3}{\pi} i_{ql} - \frac{3}{\pi} i_{qr} \tag{46}$$

B. *Linearlization and Eigenvalue Analysis*

With the rotor circuit connected to an ideally controlled power converter, rotor dynamics can be ignored, thus the overall system is modeled by (39),(40),(41) and(46). The small signal linearized version follows:

$$p\delta\lambda_{ds} = -\frac{r_s}{L_s}\delta\lambda_{ds} + \frac{r_s L_m}{L_s}\delta i_{dr} - \sqrt{2} v_m cos(\theta_0)\delta\theta \tag{47}$$

$$p\delta\theta = \frac{r_s L_m}{2L_s}\frac{\delta i_{qr}}{\lambda_{ds0}} - \frac{r_s L_m}{2L_s}\frac{i_{qr}}{\lambda_{ds0}^2}\delta\lambda_{ds} - \frac{\sqrt{2} v_m sin(\theta_0)\delta\theta}{2\lambda_{ds0}} - \frac{\sqrt{2} v_m cos(\theta_0)\delta\lambda_{ds}}{2\lambda_{ds0}^2} \tag{48}$$

$$p\delta\omega_r = -\frac{1}{2H}\frac{3}{2}\frac{P}{2}\frac{L_m}{L_s}(i_{qr0}\delta\lambda_{ds} + \lambda_{ds0}\delta i_{qr}) - \frac{1}{2H}\delta T_L - \frac{B_M}{2H}\delta\omega_r \tag{49}$$

$$p\delta V_d = \frac{3}{\pi c}\delta i_{ql} - \frac{3}{\pi c}\delta i_{qr} \tag{50}$$

Equations (47) through (50) can be arranged into the standard state equations (16), in which $x = [\delta\lambda_{ds}\ \delta\theta\ \delta\omega_r\ \delta V_d]^T, u = [\delta i_{qr}\ \delta i_{dr}\ \delta i_{ql}\ \delta i_{dl}\ \delta T_L]^T$.

It can be seen from (47) through (50) that the eigenvalues are functions of d-axis stator flux λ_{ds0}, q-axis rotor current i_{qr0}, and the stator flux initial angle θ_0. At steady-state, the flux λ_{ds0} is almost a constant, constrained by the stator voltage, while the q-axis rotor current i_{qr0} is proportional to operating torque T_{e0}. Therefore, eigenvalues would be functions of both θ_0 and T_{e0}.

However, by observing (33), it can be seen that for small disturbances, which enable the use of the small displacement method, θ_0 is small, since field orientation modeled is a continuous process, making q-axis stator flux small, thus the transient rotation angle of the reference frame is small. As a result, $v_{ds} \approx 0, v_{qs} \approx \sqrt{2} v_m$.

From (50), where both δi_{ql} and δi_{qr} are control variable displacements, it is obvious that the eigenvalue associated with V_d is zero, which is undesirable. Thus the inputs i_{ql} and i_{qr} should compensate for this marginal stable state. As shown in [2], stability of the dc bus can be maintained by controlling the network side converter such that the slip active power flows through the converters almost instantaneously. Other methods to stabilize the dc bus include designing a dc bus feedback compensator.

With the dc bus stabilized, eigenvalues of the reduced order A matrix obtained from (47) to (49) are computed for different types of torque, over the entire speed range, as shown in Fig. 5. Note that there is no complex eigenvalue.

From the computed eigenvalues, it can be observed that the eigenvalues does not depend on speed (or torque). The existence of positive eigenvalues in all situations indicates that the model (47) through (50) represents a system that is unstable during the entire speed range, for all types of torque.

C. *Discussions*

As indicated by the eigenvalue analysis, the field orientation control can be unstable. This is examined in this section.

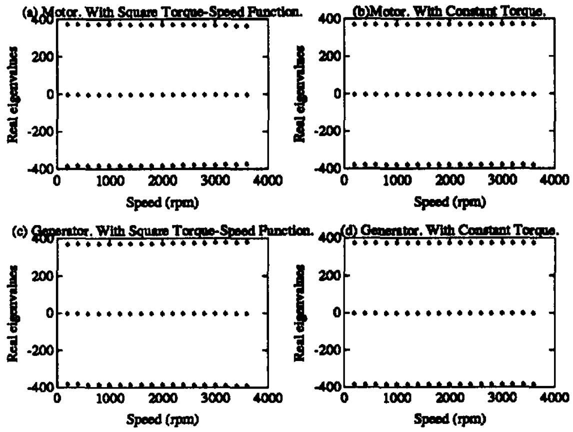

Fig.5 Real Parts of Eigenvalues of Field Oriented System

1. The validity of modeling field orientation process to get a unified machine model needs to be further examined. At first glance, this modeling is just constantly switching the reference frame, or system "observation platform", thus no "control" is really involved at all. Yet in fact, the essence of usual field orientation concept is modeled, such that in steady state, flux and torque are decoupled and furthermore, affected only by one current component, i.e. i_{dr} and i_{qr} respectively. This will become clear if one examines (39) and (41). Note that during transients, the stator flux is also slightly affected by i_{qr} through v_{ds}, indicated by (39) and (40).

   The role of θ is important in the following analysis. It is defined as the transient rotating angle of the stator flux, and it is a function of time. By modeling dynamics of θ, flux angle instantaneous and continuous dynamics has been modeled, instead of assuming idealized "jump" from the old reference frame to the new one.

2. The source of instability can be identified. In Fig. 5, two eigenvalues are actually located almost at $\pm\omega_e$, the stator voltage frequency, while the other eigenvalue locates at almost 0. This observation can be justified by approximating (47) through (49), by letting $r_s \approx 0$,$sin(\theta_0) \approx 0$ and $cos(\theta_0) \approx 1$, to get the system matrix

$$A = \begin{pmatrix} 0 & -\sqrt{2}v_m & 0 \\ -\frac{\sqrt{2}v_m}{2\lambda^2_{ds0}} & 0 & 0 \\ -\frac{1}{2H}\frac{3}{2}\frac{P}{2}\frac{L_m}{L_s}i_{qr0} & 0 & -\frac{B_m}{2H} \end{pmatrix} \quad (51)$$

   while the state vector $x = [\delta\lambda_{ds}\ \delta\theta\ \delta\omega_r]$. It can then be shown that the eigenvalues are

$$-\frac{B_m}{2H} \approx 0 \quad \frac{v_m}{\lambda_{ds0}} \approx \omega_e \quad -\frac{v_m}{\lambda_{ds0}} \approx -\omega_e \quad (52)$$

   The first eigenvalue associates with $\delta\omega_r$, while the last two associate with $\delta\lambda_{ds}$ and $\delta\theta$, which are the unstable states. This is true when the transients in θ is not properly damped, i.e. the reference frame does not follow the stator flux fast enough. Also note that even though the stator flux is almost constant in steady-state, it is not if transient occurs, including small disturbances.

3. With the reference frame tracking the stator flux instantaneously, the flux angle variation becomes 0, thus from (47), the stator flux is stabilized, and controllable through i_{dr}. And with the stator flux magnitude stabilized, typically kept at a constant value, the system becomes stable. In (49), with $\delta\lambda_{ds} = 0$, the eigenvalue associated with $\delta\omega_r$ is obviously negative, and speed displacement is affected by load torque displacement and displacement of q-axis rotor current, in addition to displacement of speed itself.

4. In reality, instantaneous reference frame tracking is not possible in computation. However, usually the computation is fast enough such that even during transients, the reference frame almost synchronizes with the stator flux, resulting in a stabilized system. On the other hand, if the computation is so slow that the reference frame fails to synchronize with the stator flux, the system becomes unstable.

5. Another means of stabilizing the system is to compensate the variations of the flux angle with the d-axis rotor current, as suggested by (47). With the variations of the stator flux properly damped, the variations of the flux angle is affected by δi_{qr}, as indicated by (48).

The above analysis is on stator field orientation control of doubly-excited machine, yet it can be extended to the schemes of field orientation control of ordinary singly-excited machines, where one recognizes that a flux regulator is always needed and computations involving field orientation should be fast enough.

The field oriented system analyzed in this section differs from the stable open-loop current control analyzed in the previous section, where the rotor current components are controlled, resulting in a controlled stator flux.

In conclusion, for the field-orientation controlled system, either the field orientation process should be fast enough in computation, or supplemental controller must be designed to compensate for the lack of sufficient system damping for flux fluctuation. As shown in our previous work [2], a torque regulator is used to produce q-axis rotor current command, and a reactive power regulator is used to produce d-axis rotor current command. Other nonlinear control techniques can also be employed to stabilize the system modeled in (39) through (46). For example, by applying input-output feedback linearization or state feedback linearization, nonlinear terms in (39) through (43) can be canceled out.

IV. Conclusions

Stability of the doubly-excited machine under open-loop voltage or current control and under field orientation control has been studied in this paper. It is concluded that with some conditions, rotor open-loop voltage and current control are both stable for both motor and generator operations. The field orientation process is stable if the computation is fast enough or if there is additional compensation. Although numerical computation for several typical types of torque and variables has been useful in revealing qualitative stability properties, an analytic derivation and more rigorous stability studies, along with thorough experimentations, are necessary for both verification and system design and evaluation.

Acknowledgment

The work in this paper is supported by a Research Initiation Grant ESC9111256 from the National Science Foundation and a Seed Grant from The Ohio State University.

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