Power Converter Sizing Considerations for a Doubly-fed Machine Propulsion Drive

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Abstract— **Doubly-fed machines (DFM) can be used to make variable speed drives (VSD) that not only provide full shaft speed control but also avoid the need for a dc electrical bus capable of providing full mechanical shaft power. This makes the DFM attractive for any VSD application where the primary power source is ac. This paper explores the design and control requirements for the DFM rotor power electronics in full-speed-range VSD applications, including propulsion drives. Trade-offs are examined for power electronics sizing versus transient settling characteristics.**

Keywords- Doubly fed machine, propulsion drive, wide speed range, inverter sizing, power capability, flux transient, flux transition controller

I. NOMENCLATURE

v_{dc}, v_{PE} : dc supply voltage & power electronics voltage rating (p.u)
i_s, i_r : Stator and rotor currents (ref. to stator) (p.u)
r_s, r_r : Stator and rotor resistances (ref. to stator) (p.u)
x_s, x_r, x_m : Stator, rotor (ref. to stator) and mutual inductances (p.u)
τ : Electromagnetic torque (p.u)
ω_B : Base frequency (same as ac supply frequency) (rad/s)
v_s, v_r : Stator and rotor voltages (p.u)
ω_s, ω_e : Stator flux frequency and rotor speed (p.u)
ω_T, ω_{max} : Transition speed between modes & maximum speed (p.u)
I_r : Rotor rated current (p.u)
δ : Angle between stator flux and stator voltage (rad)
ψ_s : Stator flux (p.u)
X_d, X_q : d and q-axis components of X
X_{dc}, X_{ac} : dc mode and ac mode values of X

II. INTRODUCTION

Doubly fed machines (DFM) have been predominantly used for applications with a limited speed range of operation such as in power generation in wind turbines and fly-wheel energy storage [1], [2]. The major advantage of using a DFM for such applications, as opposed to squirrel cage or synchronous motors, is that it requires reduced power electronics capability. However, in applications where a wider speed range is desirable, as in propulsion, typical approaches to power electronics and source connection fail to provide reduced power electronics rating.

In applications where both an ac supply is available and a dc bus is available or can be made, there is an opportunity to use a DFM drive with reduced power electronics yet operate over a full range of shaft speed. For example, in a ship, the power generation unit is typically an ac source. Electric ship propulsion drives are under increasing examination for ship propulsion [3]. Variable speed drives (VSD) might also be of great interest in other transportation systems like diesel electric trains, and for large land-based applications like chillers, HVAC fans, and pumping where the ac main is available.

The proposed drive, shown in Fig. 1, has two modes of operation; dc or low speed mode, and ac or high speed mode. In dc mode, the stator of the DFM is connected to a dc supply and the machine is equivalent to a wound field synchronous machine. In ac mode at higher shaft speeds, the stator of the DFM is connected to the ac supply and the rotor is driven by variable frequency power electronics. This arrangement can be controlled to operate the machine in and through the two modes [4].

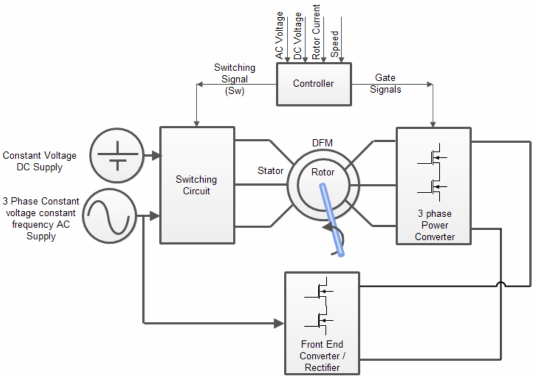

Fig. 1. Proposed confirguration of DFM drive enabling wide speed range application with reduced power electronics

For a typical ship propulsion drive, the steady-state load torque requirement is proportional to the square of the shaft speed. Based on mechanical requirements, the maximum commandable shaft torque required in the "low speed" region can be either the same as or lower than the rated torque in the "high speed" mode. The desired torques in each of the two modes and the speed transition point are design variables that

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directly affect the sizing of the rotor power electronics which is explored in this paper. This paper will discuss drive design procedures for the proposed drive architecture. The process will be illustrated using a demonstration DFM with practical machine parameters. The paper will also illustrate that the choice of transition speed between the operating modes, dc mode stator voltage, ac mode synchronous speed, maximum speed, ac mode reactive power capability, and stator flux transition control are not only dependent on the machine parameters but also on each other.

III. DFM CAPABILITY ANALYSIS

Power converter sizing will be analyzed using steady-state considerations. Transient analysis will also be conducted for situations where transient demands impact sizing of the drive. A steady-state DFM machine model in stator flux orientation can be derived ignoring the time-derivative terms in the machine model [4]. Using normalized variables and parameters with respect to base quantities, the machine can be described by:

$$v_{sd} = r_s i_{sd} \tag{1}$$

$$v_{sq} = \omega_s \psi_s + r_s i_{sq} \tag{2}$$

$$v_{rd} = r_r i_{rd} - (\omega_s - \omega_e)\psi_{rq} \tag{3}$$

$$v_{rq} = r_r i_{rq} + (\omega_s - \omega_e)\psi_{rd} \tag{4}$$

while the normalized electromagnetic torque is governed by:

$$\tau = -\frac{x_m}{x_s}\psi_s i_{rq} \tag{5}$$

and the normalized flux linkage equations are:

$$\psi_s = x_s i_{sd} + x_m i_{rd} \tag{6}$$

$$0 = x_s i_{sq} + x_m i_{rq} \tag{7}$$

$$\psi_{rd} = x_r i_{rd} + x_m i_{sd} \tag{8}$$

$$\psi_{rq} = x_r i_{rq} + x_m i_{sq} \tag{9}$$

The rotor quantities used in the model are reflected to the stator. Therefore, to obtain actual rotor values, the turns-ratio from stator to rotor must be considered. The rated voltage and current of the stator are considered to be base quantities, and hence are unity in normalized form. The ac supply frequency is chosen as the base quantity for the stator flux frequency and rotor speed. This makes normalized stator flux frequency, ω_s, zero in dc mode and unity in ac mode.

A. Ideal DFM

As precursor, an analysis of an ideal DFM is considered to illustrate the dependency of choice of transition speed and maximum speed with minimum rotor power electronics for a required electromagnetic torque profile.

Assuming zero resistances, leakages and negligible magnetizing current, the normalized rotor current rating (reflected to the stator) is equal to the stator current rating of unity. Using (3), (4), (6) - (9), the rotor voltage required is,

$$v_r = |\omega_s - \omega_e|\psi_s \tag{10}$$

The operating stator flux in the ac mode is determined by the ac supply voltage and frequency and hence is always unity. For maximum utilization of the DFM, the rotor current rating of the DFM sets the current rating of the rotor power electronics. Unity rotor current and stator flux ensures that maximum torque capability of the DFM is utilized in the ac mode.

The choice of stator flux in the dc mode depends on the acceptable torque requirement in low speed mode. For a unity torque requirement in low speed mode, the rotor current and the stator flux must be maintained at unity. If dc mode stator flux is unity, then required rotor voltage is proportional to speed in dc mode, and proportional to slip speed in ac mode as shown in Fig. 2. As a concrete example, a transition at ‘A’ from dc to ac mode will ensure operation of the drive from zero to 1.5 p.u speed while requiring a maximum rotor voltage of 0.5 p.u (operating on OAEB path in Fig. 3).

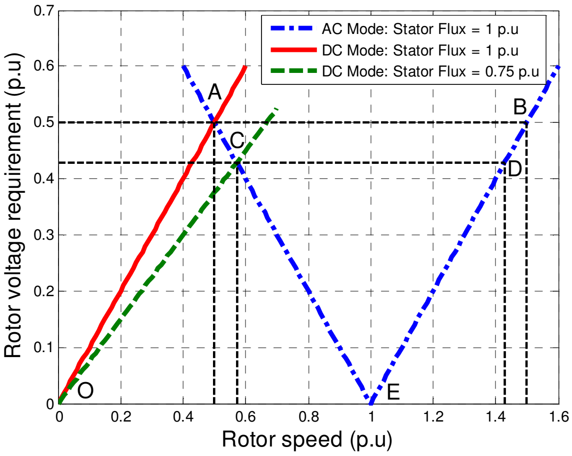

Fig. 2. Ideal DFM: Rotor power electronics voltage rating of 0.5 p.u can enable operating speed range of 0 to 1.5 p.u (OAEB)

If a lower electromagnetic torque is acceptable at low speed, for example 75% to that of high speed, the stator flux in dc mode can be reduced to 0.75 p.u. while maintaining the rotor current at unity across the complete speed range. The reduction in stator flux in the dc mode directly impacts the required rotor voltage since the slope of the rotor voltage requirement curve in Fig. 2 is proportional to the stator flux. In this case, transitioning at ‘C’ enables to operate on a speed range from zero to 1.43 p.u while requiring a maximum rotor voltage of 0.43 p.u. (OCED path). In general, the transition speed that minimizes the maximum required rotor voltage can be computed equating required voltage in the dc and ac mode at the transition point using (10) i.e;

$$v_{rdc}\big|_{\omega_T} = |-\omega_T|\psi_{sdc} = |1-\omega_T| = v_{rac}\big|_{\omega_T} = v_{PE} \tag{11}$$

Since the rotor current is maintained at unity for maximum torque production, the stator flux magnitude in dc mode (ψ_{sdc})

is identical to the maximum torque in dc mode (τ_{dc}) and (11) simplifies to,

$$\omega_T = \frac{1}{\tau_{dc} + 1} \qquad (12)$$

Using (10) and (12), the minimum required rotor power electronics voltage rating is given by,

$$v_{PE} = \frac{\tau_{dc}}{\tau_{dc} + 1} \qquad (13)$$

Using (10) in ac mode and (13), the associated maximum achievable shaft speed in ac mode with the minimum rotor power electronics voltage rating can be computed as,

$$\omega_{\max} = \frac{2\tau_{dc} + 1}{\tau_{dc} + 1} \qquad (14)$$

Assuming no mechanical losses, the maximum shaft power is achieved at the maximum speed and is identical to (14) since the torque at maximum speed is unity. The minimum rotor power electronics power rating is identical to (13) since the rotor current is always maintained at unity. When the required dc mode torque is 75% to that rated torque, the minimum rotor power electronics rating can be 30% of maximum shaft power while operating on a speed range of 0-1.43 p.u. Equation (13) and (14) can be used to compute the ratio of v_{PE}/ω_{max}, which is also the ratio of minimum rotor power electronics rating to maximum shaft power given unity rotor maximum current and maximum shaft torque. Fig. 3 shows the benefit and the design trade-offs for the proposed drive architecture using (13) and (14).

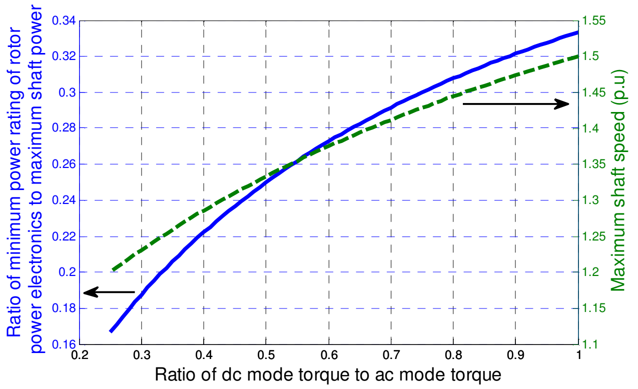

Fig. 3. Ideal DFM: Lowering requirement of dc mode torque lowers required rotor power electronics rating and maximum shaft speed (if ac supply frequency is constant)

In cases where the ac supply frequency can be chosen, e.g., a "blank slate" design for a ship or train, for example, then the ac frequency can be chosen to satisfy maximum speed requirement for the drive. In cases where the ac supply frequency is fixed, the maximum speed will be set by the minimum voltage rating of the rotor power electronics. Increase in maximum speed requirement will increase the voltage rating of the rotor power electronics. To summarize, for proper utilization, the torque capability of the DFM must be equal to the required torque at high speed. Since in ac mode the stator flux is strictly determined by the ac supply voltage and frequency, the choice of high speed torque strongly influences the rotor power electronics **current** rating. The choice of low speed mode torque strongly influences rotor power electronics **voltage** rating (since fixing rotor current to be same as in ac mode, the dc mode stator flux can be altered). The torque requirements significantly influence the transition speed, the maximum speed and, of course, the rotor power electronics power rating.

B. Non-ideal DFM

The presence of resistances, leakages and finite magnetizing current in a practical DFM must be taken into account while minimizing the rotor power electronics rating such that the machine is operated within its rated capability. In practice, the stator and rotor current ratings might not be equal, and hence the rated stator current is chosen as the base current for normalization, whereas the rated rotor current reflected to the stator is designated as I_r p.u. This section will review design considerations for a practical DFM propulsion drive. Specific examples will be illustrated using parameters from our experimental machine shown in Table I. These parameters are not representative of a real ship propulsion motor.

TABLE I. DFM PARAMETERS

Parameter	Actual	p.u
Stator resistance	3.575 Ω	0.1013
Rotor resistance (ref. to stator)	4.229 Ω	0.1199
Stator leakage inductance	9.6 mH	0.1024
Rotor leakage inductance (ref. to stator)	9.6 mH	0.1024
Mutual inductance	165 mH	1.7630
Stator current rating	5.09 A (peak)	1
Rotor current rating (ref. to stator) (I_r)	3.857 A (peak)	0.7576

Our goal will be to minimize the rotor power electronics requirements while the machine operates with maximum torque capability at rated conditions. The sizing of the rotor power electronics starts with selecting the rotor power electronics current rating such that the candidate DFM is utilized to its maximum capability in ac mode. Once the current rating is determined, the allowable limits on the d and q-axis rotor current in ac mode can be computed. Then the rotor power electronics voltage rating, dependent on the torque requirement in dc mode, can be set. Finally the transition speed and the maximum speed are set to minimize the power rating of rotor power electronics.

1) AC Mode: Choice of rotor power electronics current rating

Due to possibility of different current ratings in the stator and rotor in a practical DFM, the rotor power electronics current must be chosen such that the machine stator and rotor current limits are not exceeded. The objective is to utilize the candidate DFM to its maximum torque capability in high speed mode. Since the stator is connected to a stiff ac voltage source,

$$v_{sd}^2 + v_{sq}^2 = 1 \qquad (15)$$

Since r_s in a typical machine is small, (15) can be simplified using (1), (2) and (7) to compute,

$$\psi_{sac} = 1 + \frac{r_s x_m}{x_s} i_{rq} \qquad (16)$$

The rotor current limit requires that

$$i_{rd}^{\ 2} + i_{rq}^{\ 2} \le I_r^{\ 2} \qquad (17)$$

The stator current limit necessitates

$$i_{sd}^{\ 2} + i_{sq}^{\ 2} \le 1 \qquad (18)$$

Using (6) and (7), the stator currents can be substituted with rotor currents in (18) that results in,

$$\left(\frac{\psi_{sac} - x_m i_{rd}}{x_s}\right)^2 + \left(-\frac{x_m i_{rq}}{x_s}\right)^2 \le 1 \qquad (19)$$

Constraints (17) and (19) are plotted in d-q rotor current axis, shown in Fig. 4, to obtain the safe operating current limits that is the area of intersection between the two constraints. The maximum torque capability of the DFM is achieved when maximum negative q-axis current can be driven into the rotor of the DFM within the safe operating area. In the example DFM, the maximum torque capability is achieved when the rotor q-axis current is identical to rotor current rating and rotor d-axis current is zero. The rotor power electronics current rating, therefore, must be equal to the rotor current rating.

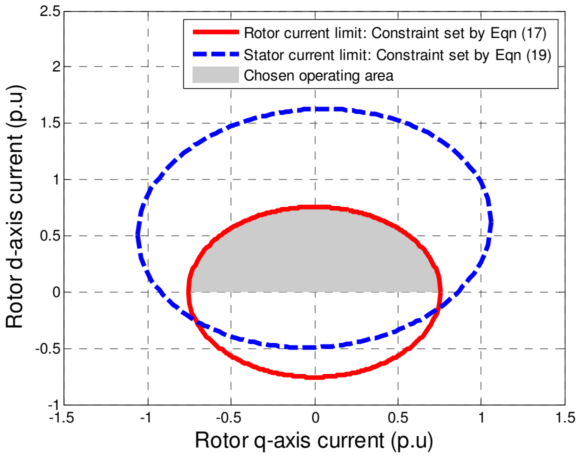

Fig. 4. AC Mode: Limits on rotor d and q-axis current that is within the machine rated limits.

2) AC Mode: Determination of maximum torque capability of the candidate DFM

With the maximum q-axis rotor current that can be driven into the rotor being known, using (5) and (16), the maximum torque capability of the candidate DFM can be computed as,

$$\tau_{\max} = \frac{x_m}{x_s}\left(1 - \frac{r_s x_m}{x_s} I_r\right) I_r \qquad (20)$$

If the torque requirement at high speed is smaller than the capability, the candidate DFM will be an oversized machine, left unutilized from the torque capability perspective. The "extra" capability may be utilized for reactive power control as will be discussed in the following section. If the torque requirement is larger than the capability, obviously, an alternate DFM design must be selected. Equations (5) and (16) can be used to plot Fig. 5, which shows the maximum torque capability of the example DFM ($\tau_{\max}$=0.663 p.u) as well as the drooping behavior of stator flux with increasing torque due to non-idealities in the machine.

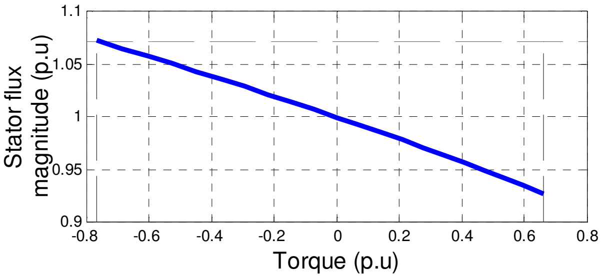

Fig. 5. AC mode: Drooping of the stator flux with torque due to presence of stator resistance and leakages for the example DFM

3) AC Mode: Choice of rotor d-axis current limit

In ac mode, a secondary objective may be to achieve power factor control on the stator when connected to the ac utility. For example, any "extra" or spare rotor inverter and DFM capability may be used achieve reactive power control of the ship micro-grid. This is an exciting opportunity to allow the drive to assist with overall power system stability, and an opportunity that may make the DFM VSD attractive in many other applications besides propulsion.

The limit of the rotor d-axis current rating, which affects stator power factor, can be obtained from the stator and the rotor current rating. From (16), (17) and (19) for a particular q-axis rotor current, the upper limit is,

$$i_{rd}\big|_{\max} \le Min\left(\sqrt{I_r^{\ 2} - i_{rq}^{\ 2}},\ \left(1 + \frac{r_s x_m}{x_s} i_{rq} + x_s\sqrt{1 - \left(\frac{x_m i_{rq}}{x_s}\right)^2}\right)\Big/ x_m\right) \qquad (21)$$

while the lower limit is,

$$i_{rd}\big|_{\min} \ge Max\left(-\sqrt{I_r^{\ 2} - i_{rq}^{\ 2}},\ \left(1 + \frac{r_s x_m}{x_s} i_{rq} - x_s\sqrt{1 - \left(\frac{x_m i_{rq}}{x_s}\right)^2}\right)\Big/ x_m\right) \qquad (22)$$

For the parameters of the example machine, the stator current limit imposes a minimum d-axis rotor current of negative value, which does not provide any benefit in ac mode. The minimum d-axis rotor current is, therefore, chosen to be zero. The chosen operating area for rotor current is shown in Fig. 4.

4) DC Mode Operation: Choice of rotor power electronics voltage rating

The design process continues with selection of required torque in dc mode, which sets rotor power electronics voltage rating. As an example, the required torque in dc mode is chosen as 75% of the ac mode torque (equivalent to 0.498 p.u for the example DFM). As the current capability of the DFM as well as the rotor power electronics are already determined, the stator flux in dc mode must be chosen such that the required torque can be achieved. The stator flux in dc mode, however, is dependent on the d-axis component of the stator current as well as the rotor current.

A design choice has to be made to provide the d and q-axis current in the rotor such that two constraints are satisfied. First, the required rotor current must not exceed the power electronics current rating. Second, the stator current rating of the machine must not be exceeded. With these two constraints, the required low speed torque should be achieved with minimum stator flux. This reduces the power electronics voltage rating. Since relatively low winding resistance will likely constrain the choice of dc voltage to keep stator current within rating, limits on the stator voltage can likely be ignored.

Assuming that the positive dc supply is connected to stator A phase while negative is connected to B and C phase, Fig. 6 shows the space vectors of stator flux and voltage.

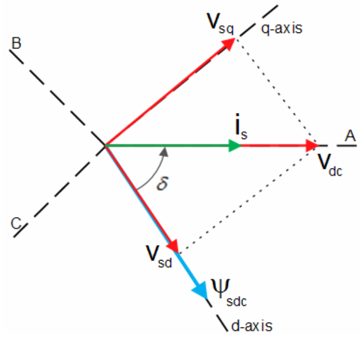

Fig. 6. DC Mode: Steady-state space vector diagram

Resolving stator voltage into d and q-axis components results in,

$$\begin{aligned} v_{sd} &= v_{dc} \cos\delta \\ v_{sq} &= v_{dc} \sin\delta \end{aligned} \qquad (23)$$

where $i_s = v_{dc} / r_s$

Using (2) & (23) in (7) and rearranging yields,

$$i_{rq} = -\frac{x_s}{x_m} i_s \sin\delta \qquad (24)$$

Similarly using (1) and (23) in (6) and rearranging results,

$$i_{rd} = \frac{\psi_{sdc}}{x_m} - \frac{x_s}{x_m} i_s \cos\delta \qquad (25)$$

The torque in dc mode can be computed using (24) in (5),

$$\tau_{dc} = i_s \psi_{sdc} \sin\delta \qquad (26)$$

For steady operation, the upper bound on δ is 90°.

To keep the machine stator current within its r.m.s rating (since the stator current is dc),

$$i_s \le \frac{1}{\sqrt{2}} \qquad (27)$$

Similarly, the rotor current must be within its rated limit which is obtained from (24), (25) and (26). However, there are two limits that must be adhered to from the rotor current perspective. First a steady-state limit,

$$i_r = \sqrt{\left(-\frac{x_s}{x_m} i_s \sin\delta\right)^2 + \left(\frac{\tau_{dc}}{x_m i_s \sin\delta} - \frac{x_s}{x_m} i_s \cos\delta\right)^2} \le I_r \qquad (28)$$

and second, a dynamic limit since δ has a dynamical response when a torque is commanded.

$$i_r = \sqrt{\left(-\frac{x_s}{x_m} i_s \sin\delta\right)^2 + \left(\frac{\tau_{dc}}{x_m i_s \sin\delta}\right)^2} \le I_r \qquad (29)$$

Equations (27), (28) and (29) can be solved for stator current with respect to load angle while considering maximum current limit, I_r and required torque τ_{dc}. These three equations imply three simultaneous bounds on maximum stator current. The lowest limit defines the capability curve for practical stator current, as shown in Fig. 7, which gives plots of the stator current limits implied by (27), (28) and (29).

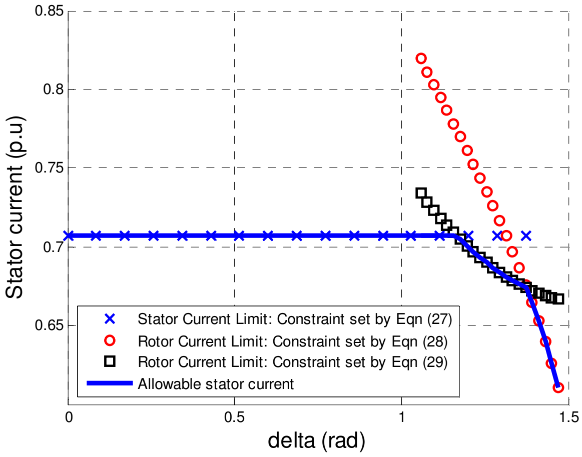

Fig. 7. Bounds on maximum allowable stator current due to stator and rotor current ratings for a chosen δ

With the bounds on stator current so obtained for a particular δ, the stator flux can be computed using (26) in order to achieve the required torque. For the required torque, higher stator current and higher δ will minimize stator flux and the minimum stator flux is obtained at the maximum allowable δ as seen in Fig. 8.

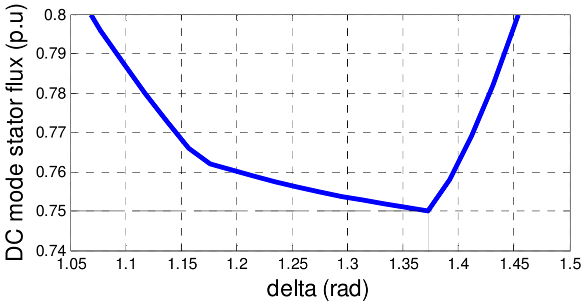

Fig. 8. The maximum operating δ is chosen such that dc mode stator flux is minimized

The minimum stator flux obtained for the example DFM is 0.75 p.u since both in ac and dc modes the limits on the rotor currents are effective. The maximum δ sets the stator current and hence the stator voltage in the dc mode.

Fig. 9 shows that the total stator and rotor currents are within the machine ratings for allowable δ and produce the maximum torque at the maximum allowable δ for the minimum dc mode stator flux. The rotor d-axis and q-axis current limits in the dc mode are different than in the ac mode and can be obtained from Fig. 9.

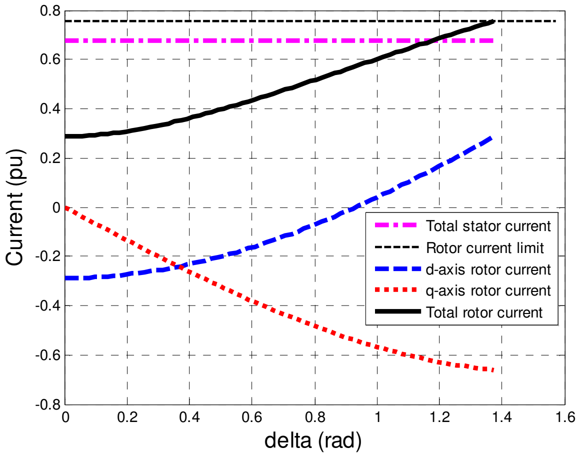

Fig. 9. DC Mode: Steady-state components of rotor current & total stator and rotor currents within limits minimizing stator flux for required torque

5) *Computation of transition speed and maximum speed*

Considering the non-ideal DFM and using the minimized stator flux in dc mode and the rotor current in the ac mode, as computed in the previous section, (1)-(9) can be used to compute the rotor voltage requirement in dc and ac modes. Comparing Fig. 3 with Fig. 10 shows the changes due to presence of non-idealities in the DFM.

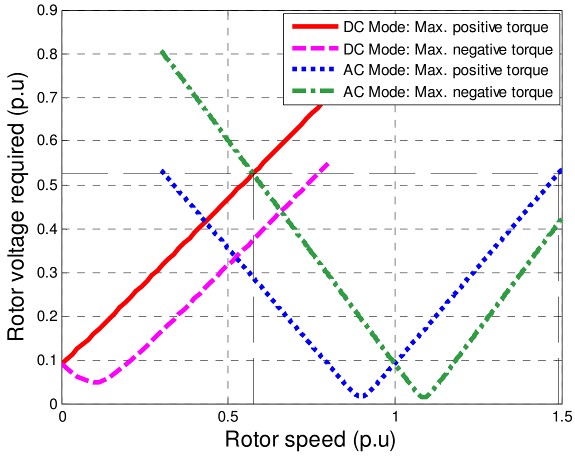

Fig. 10. Example DFM: Rotor power electronics voltage requirement depends on whether the drive is making positive or negative torque

First, non-zero voltages are required at zero and unity speed. Second, the voltage requirement for the rotor depends on whether the torque demand is positive or negative. Third, the slope of the voltage requirement in ac mode is dependent on torque since the stator flux varies with torque as observed in Fig. 5. To minimize required rotor voltage to operate the drive under all operating conditions, a suitable transition speed is chosen such that required rotor voltage in dc mode for maximum positive torque equals that in ac mode for maximum negative torque. The maximum speed of operation can be obtained based on the chosen minimum rotor voltage and voltage requirement in ac mode for maximum positive torque. Fig. 11 shows the rotor voltage profile required during maximum positive and negative torque with the rotor voltage limit set to 0.525 p.u while operating on a speed range of 0-1.49 p.u.

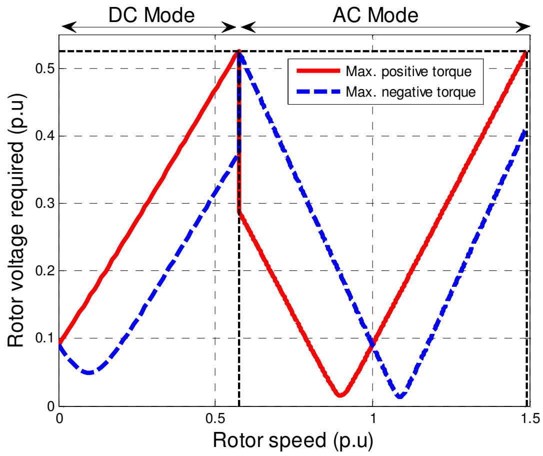

Fig. 11. Example DFM: 0.525 p.u rotor power electronics voltage rating can enable operation from 0 to 1.49 p.u speed

Fig. 12 shows the sharing of total active power between the stator and rotor for the non-ideal DFM. Rotor power electronics of 0.3475 p.u can be used to control the maximum active power being fed to the DFM as compared to 0.3 p.u as computed for an ideal DFM. Depending on the efficiency of the DFM and the mechanical drive train, the shaft power can be calculated.

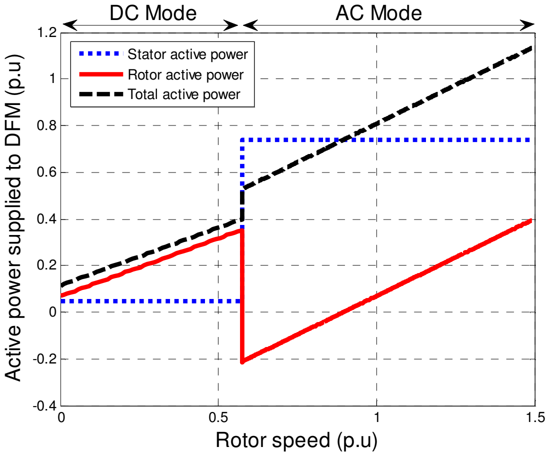

Fig. 12. Example DFM: Rotor power electronics of 0.347 p.u power rating can control the net active power operating on a speed range of 0-1.49 p.u

Fig. 13 shows the steady-state torque-speed capability of the example DFM with the proposed drive architecture. A typical propulsion load torque is also shown that is proportional to the square of rotor speed and matches the maximum torque capability of the DFM at maximum speed.

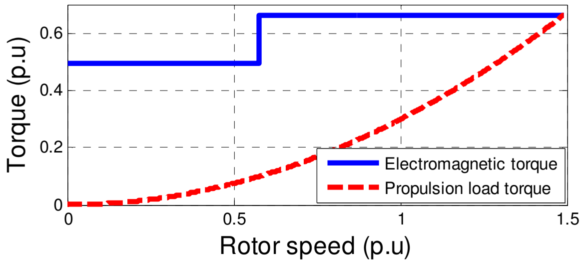

Fig. 13. Steady-state torque-speed capability of the example DFM using the proposed drive with a typical propulsion load torque

IV. TRANSIENT ANALYSIS

A dynamic analysis of the proposed drive is required in order to ensure that the power electronics are designed with sufficient capability to drive the machine through the transition between modes without undesirable shaft and power disturbances. During the ac to dc mode transition, the stator flux controller [4] can control the flux and have a smooth transition of stator flux magnitudes. However, during the dc to ac mode transition, a detailed analysis is important since in ac mode, the stator flux is uncontrolled and is set by the ac supply. Although [4] details an empirical controller for stator flux transition, a formal analysis is presented here including controller design, which shows the importance of the stator flux transient on drive sizing.

A. *Non-linear model for flux transition*

Assuming that the current controller bandwidth is sufficiently high and the speed controller bandwidth is sufficiently low, the dynamics involved in the dc to ac mode transition can be simplified with two state variables: the stator flux magnitude and the angle between the stator flux and the stator voltage. Incorporating the dynamics in (1) and (2) and recognizing that the stator voltage frequency is unity yields,

$$\frac{1}{\omega_B}\frac{d}{dt}\psi_s = v_{sd} - r_s i_{sd} \tag{30}$$

$$\frac{1}{\omega_B}\frac{d\delta}{dt} = 1 - \frac{v_{sq} - r_s i_{sq}}{\psi_s} \tag{31}$$

Using (6) and (7) and noting that in ac mode,

$$v_{sd} = \cos\delta$$

$$v_{sq} = \sin\delta$$

(30) and (31) can be rearranged as,

$$\frac{1}{\omega_B}\frac{d}{dt}\psi_s = \cos\delta - \frac{r_s}{x_s}\psi_s + \frac{r_s x_m}{x_s} i_{rd} \tag{32}$$

$$\frac{1}{\omega_B}\frac{d\delta}{dt} = 1 - \frac{1}{\psi_s}\sin\delta - \frac{1}{\psi_s}\frac{r_s x_m}{x_s} i_{rq} \tag{33}$$

The initial value of the stator flux magnitude is obtained from dc mode while the initial value for the angle is obtained from the switching instant from dc to ac mode as determined by the synchronizer [4].

The autonomous response of the non-linear system during the dc to ac mode transition is shown in the phase plane plot in Fig. 14. In ac mode, the d-axis rotor current is set to zero and q-axis rotor current is commanded based on required torque. Although the transition is stable, there are two important observations. First, the maximum stator flux that can be handled by the rotor inverter based on the steady-state design can be seen in Fig. 5, and is marked in Fig. 14. That is, if the stator flux is higher than the designed value, the rotor power electronics will be voltage limited and will not be able to control the rotor current resulting undesirable torque and power disturbances.

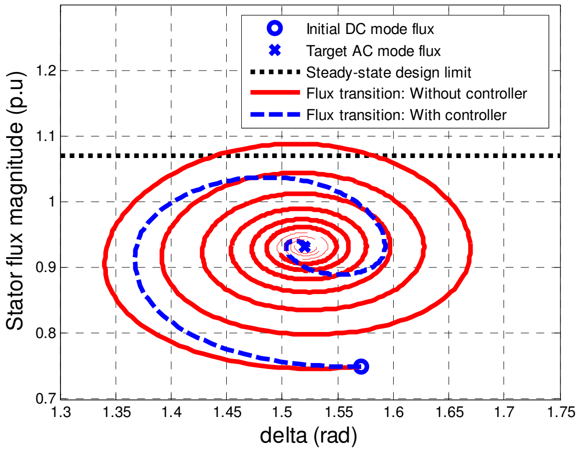

Fig. 14. Phase plant plot: Flux transition from dc mode to ac mode with and without flux transition controller

Second, there is sloshing of power back and forth between the stator and the ac power supply each time the stator flux goes above and below the steady state flux level, respectively. Since the q-axis current is predominantly used to control the torque of the DFM under all operating modes, the d-axis current can be used to control the flux transition from dc to ac mode to the extent possible within the allowable limits.

B. *Model linearization and flux transition controller design*

In order to develop stator flux transition controller, the non-linear model, described by (32) and (33), is linearized across the ac steady-state operating point such that, $\psi_s = \Psi_s + \tilde{\psi}_s\,;\delta = \Delta + \tilde{\delta}\,;i_{rq} = I_{RQ} + \tilde{i}_{rq}\,;i_{rd} = \tilde{i}_{rd}$

The linearized model obtained is:

$$\frac{1}{\omega_B}\frac{d}{dt}\tilde{\psi}_s = -\tilde{\psi}_s\frac{r_s}{x_s} - \tilde{\delta}\sin\Delta + \frac{r_s x_m}{x_s}\tilde{i}_{rd} \tag{34}$$

$$\frac{1}{\omega_B}\frac{d\tilde{\delta}}{dt}=\tilde{\psi}_s\left(\frac{\sin\Delta}{\Psi_s{}^2}+\frac{r_s x_m I_{RQ}}{\Psi_s{}^2 x_s}\right)-\tilde{\delta}\frac{\cos\Delta}{\Psi_s}-\frac{r_s x_m}{\Psi_s x_s}\tilde{i}_{rq} \quad (35)$$

A full state feedback controller (two input one output) is designed based on the linearized model and is used to command the d-axis current during transition. The controller can not only damp the oscillation but can also reduce the maximum perturbation of stator flux magnitude, as shown in Fig. 14, thereby enabling current control on the rotor even during transition. The limit on rotor d-axis current imposes the limit on the maximum possible damping.

V. EXPERIMENTAL RESULTS

A 1 HP, 220 V/ 150 V, 60 Hz, 4 Pole DFM has been used to illustrate the validity of the considerations discussed above. The experimental setup is identical to the one as described in [4] and parameters for the machine were presented in Table I. The ac supply is programmed to have 28 V, 12 Hz whereas the dc supply is programmed to have 10 V. Since the DFM is run under different operating voltages, the models described in the previous section are used to simulate the behavior at the chosen operating condition. The models are additionally corrected for device and brush drops.

A. *Rotor voltage requirement: During acceleration and deceleration*

Fig. 15 shows the rotor voltage requirement when a step command in speed of 1.5 p.u is given. Once steady-state is reached, zero speed is commanded. The mode transition speed is set at 0.6 p.u. Experimental waveforms are filtered using a median filter in MATLAB™ for clarity. Voltage requirement for acceleration has more data points than during deceleration since acceleration time is longer than deceleration time.

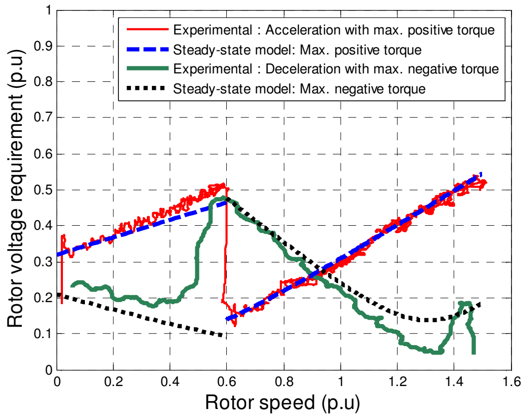

Fig. 15. Comparison of model with experimental results during acceleration and deceleration

B. *Evaluation of stator flux transition controller*

Fig. 16 shows the stator flux transition during mode transition from dc (0.4 p.u) to ac (0.8 p.u). The model and experimental results match closely. The minor deviations in the estimated and actual values can be due to parametric sensitivity, speed variation and robustness of estimation of stator flux magnitude and angle.

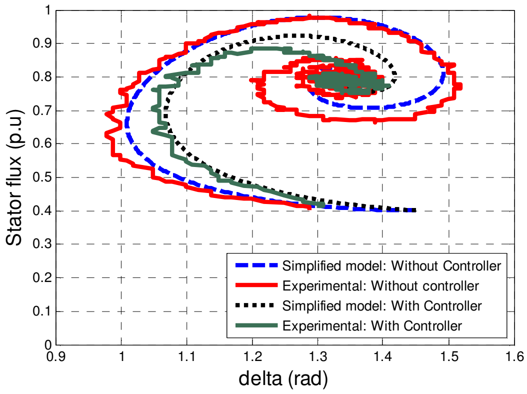

Fig. 16. Phase plane plot: Comparison of model with experimental results during dc to ac transition with and without stator flux transition controller

VI. CONCLUSION

This paper discussed a design process for a DFM drive. Two mode operation permits full speed range VSD when an ac utility is available. While ac mode operation impacts the current rating, dc mode operation impacts the voltage rating of the rotor power electronics. Given a DFM and torque requirements, the rotor power electronics can be minimized with proper choice of transition speed between modes and maximum desirable speed. Although an exemplary design has been shown with a propulsion load torque profile, the design can be iterated for other desirable load torque profiles like traction, which require higher torque in low speed and lower torque in high speed. Using similar drive architecture but designing for higher dc mode torque compared to ac mode torque can satisfy the traction torque requirement. The drive architecture also provides flexibility of introducing a third mode, “high speed dc” mode, when the ac mode can be switched back to dc mode but with lower effective stator flux allowing a field weakening operation.

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