Switched Doubly-fed Machine Propulsion Drive

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Abstract—**Variable speed drives (VSD) constructed with doubly-fed machines (DFM) offer interesting flexibility for power electronic drive design. They also offer opportunities for controlling interactions with an ac grid. Design options are most flexible for the VSD DFM when the machine stator can be operated from an ac or dc source, selected "on-the-fly" as appropriate. This paper presents a SCR-based transfer switch that can connect the stator of the DFM either to an ac source or a dc source "on-the-fly". Current commutations of the SCRs and a "bumpless" transition in shaft behavior is controlled from the rotor.**

I. NOMENCLATURE

I_S	: Stator current vector (A)
P	: Number of poles
R_s	: Stator resistances (Ohms)
Sw	: Switching signal for ac-dc mode changeover
τ	: Electromagnetic torque (N-m)
V_{AC},V_{DC}	: ac and dc source voltage vector (V)
ω_{ac}	: ac supply frequency (rad/s)
δ	: Angle between stator voltage vector and stator flux vector
ψ_S	: Stator flux space vector (V-sec)
X_d, X_q	: d and q axis components of any variable X
X_{AC}, X_{DC}	: ac mode and dc mode value of any variable X

II. INTRODUCTION

Variable speed drives (VSD) are critical in many industrial and commercial applications. They are increasingly relevant not only for process or motion control, but also for optimizing energy consumption, e.g., in HVAC units. The demand for efficient, cost-effective and sustainable solutions for different industrial sectors has led to larger market penetrations of high power VSDs [1]. Essentially all machine types have been explored for high power VSDs including squirrel-cage induction, synchronous, permanent magnet, doubly-fed induction and super-conducting [2]-[3]. At higher voltage and current levels, e.g., for machines in the megawatt range and beyond, power electronic converters become a challenge for creating a VSD. VSD power converters at higher power levels may require multiple semiconductor devices in series and parallel due to the limited available ratings. Switching at several hundred Hz becomes essential to limit the switching losses in the devices leading to poorer dynamic performance and higher harmonic distortion of the motor and the line side waveforms of the drive [4].

A doubly-fed machine (DFM) offers interesting possibilities for reducing the required rating of associated power electronic controls. This has made the DFM attractive,

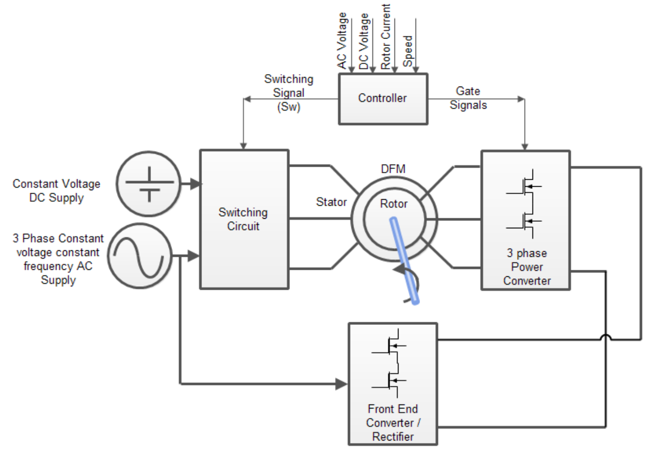


Figure 1. Proposed confirguration of DFM drive.

for example, in wind generation applications where a limited range of operating speed around synchronous speed substantially reduces the required power converter size (typically to 1/3rd compared to that of the electrical machine size). However this reduction is lost or muted if the required operating speed range of the drive is increased.

In applications where a dc source is available or can be made from an existing ac source, as in a ship propulsion drive, the DFM drive can be configured as shown in Fig. 1 enabling reduced power electronics converter rating while operating over a full speed range down to zero speed. The drive operates in one of the two modes: dc mode - at low speed, the stator of the DFM is connected to the dc source, making the DFM behave as a wound-field synchronous machine; and ac mode - at higher speed, the stator is switched to the fixed frequency ac supply transforming the DFM to the traditional doubly-fed induction machine. The rotor of the DFM is always fed from a controlled converter. The rotor power electronics converter rating can be 1/3rd of the machine power rating while operating on a speed range of 0-1.5 p.u (normalized to synchronous speed corresponding to the ac source frequency) [5]. Further, changing the phase sequence of the ac source connection to the stator extends the operating speed range of the drive to ±1.5 p.u enabling a four-quadrant operation of the proposed drive with the same rotor power electronics power rating. Reduction of controlled power electronics requirement

978-1-4799-2325-0/14/$31.00 ©2014 IEEE

translates into savings on transformer and filter size for the overall drive which are costly and bulky components at high power [5].

The proposed drive can be controlled in and through the two modes with essentially "seamless" mechanical shaft behavior [6]. A critical challenge for practically implementing such a drive remains on the development of a cost-effective switching circuit that can connect the stator to either of the sources, dc or ac, on-the-fly and reversibly. A complex switching circuit in the DFM stator made with self-commutating devices like IGCT, GTO, IGBT may counter the benefit of reduced power electronics on the rotor. On the other hand, sluggish mechanical switches controlling the stator connection can significantly impact the shaft behavior during transition, leading to poorly controlled speed/torque variations [7]. Using SCRs for the stator transition between ac and dc voltages can provide balance between complexity and performance. SCR are still some of the most capable high power devices available. They can handle large currents and block large voltages with a single device. However, SCRs require special consideration to ensure device turn-off.

This paper presents a SCR-based static transfer switch (STS) that can connect the stator of the proposed DFM drive either to the ac or the dc source "on-the-fly" with well-controlled speed/torque variations at the shaft output. Two sets of SCRs are used to connect the sources to the stator of the DFM. One set is turned 'ON' during individual operating mode of the DFM drive to connect the source to the stator. The dc-side SCRs do not switch when the DFM drive is operating in the dc mode whereas the ac-side SCRs switch at line frequency in the ac mode of operation of the DFM drive. This minimizes switching losses in the overall transfer switch without increasing harmonic distortions of the stator waveform. During the mode transition, careful control of the rotor power electronics not only ensures natural commutation of the "outgoing" SCR set but also makes a mechanically "bumpless" transition at the shaft.

The analysis performed for the development of the STS suited for the DFM drive is based on three levels of analysis. First, a simple SCR-based switching circuit is reviewed that can interchange the connection of a constant current load between two arbitrary sources. This analysis helps in formulating the commutation requirement of the "outgoing" SCR based on current polarity and source voltage magnitudes. Second, the simple SCR-based switching circuit is extended to three phase source connections of the load where one source is an ac while the other is a dc. The analysis results in identifying specific regions during ac cycle where all the three phases can switch simultaneously with natural commutation. Finally, available rotor power electronics control is utilized to ensure a mechanically "bumpless" transition for the DFM drive with natural commutation of the "outgoing" SCR bank under different mechanical loading condition at the shaft.

III. STATIC TRANSFER SWITCH ANALYSIS

SCR-based static transfer switches have been used extensively for selecting between multiple ac sources for serving a critical load [8],[9]. They are also a part of solid state relays. However, for the proposed DFM drive, the transfer occurs between an ac and a dc source of widely different voltage magnitudes with the load having variable power factor and regeneration capability. This is a challenge since neither the two sources are "synchronized" for transfer nor the load, in this case the DFM, can withstand partial phase transfer [10].

This section begins with a review of the ideal requirement for a transfer between an ac and a dc source for the stator of the DFM VSD. Analyzing a simple constant current load transferring between two arbitrary sources identifies commutation requirement which forms the basis of the next layer of complexity where three phases are introduced for the transfer switch. For the three phase SCR based STS, regions are identified in an ac cycle such that all the three phases can undergo simultaneous natural commutation during source transition.

A. Requirements for an ideal transfer switch

A schematic of an ideal transfer switch, replacing the switching circuit in Fig. 1, connected to the DFM is shown in Fig. 2. The DFM can be connected to either of the two sources, ac or dc, based on the configuration of 'S1' and 'S2'. It is assumed that the dc and the ac sources share a common reference. The dc source is assumed only to source, not sink current.

Several characteristics of operation of the transfer switch are required:

- The ac and dc sources should not be shorted i.e 'S1' and 'S2' cannot be 'ON' simultaneously.
- The three phases should always switch together i.e, the three phases of the stator are connected to a single source, either dc or ac, at any instant of time. This helps to ensure that the DFM will not experience severe unbalance stator voltages and an associated unacceptable disturbance in the stator flux.
- The DFM stator current should not be interrupted instantaneously i.e. switch 'S1' and 'S2' cannot be both 'OFF' abruptly while the load current is nonzero.

A few other characteristics are also highly desirable:

- The DFM should experience minimal perturbation in electromagnetic torque/speed at the shaft.

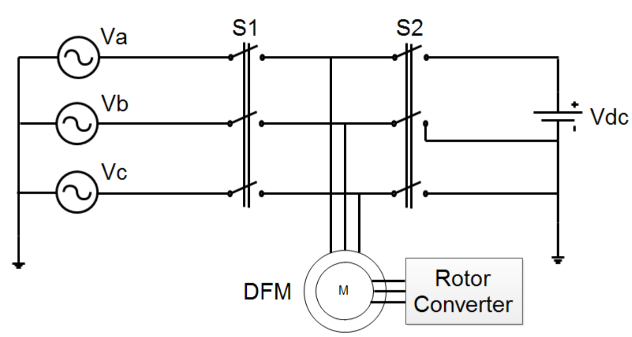


Figure 2. Ideal transfer switch connected to the DFM stator winding to alter the connection between ac and dc sources as necessary based on operating speed.

- Requirements for additional "supporting" circuitry, e.g., for ensuring commutation, should be minimized to limit cost and complexity.

Since the switch 'S1' needs to block bidirectional voltage and allow bidirectional current, an anti-parallel configuration of SCRs for each phase is desirable. The switch 'S2' needs to carry only unidirectional current and block bidirectional voltage, so a single SCR for each phase is sufficient.

B. Single cell analysis for commutation requirement

A simplified version of the switch is evaluated for its commutation requirements. These familiar results for a constant current load are essential for extending the analysis to three phase sources of different form, ac and dc, with the DFM as the load. Figure 3 shows the single cell of the SCR based transfer switch connected to a constant current load. The load can be connected to arbitrary voltage sources V_X and V_Y reference to a common ground.

Assuming initially the load is connected to source V_X, a transition to source V_Y is desired. Four well-known commutation scenarios arise based on the load current polarity and the relative magnitudes of V_X and V_Y.

Case I: $V_Y > V_X$ & $I_L > 0$

As the load current is positive, SCRs 'T_{XR}' and 'T_{YR}' are non-functional and their gate control is permanently disabled. Load current initially flowing in 'T_{XF}' *naturally commutates* to 'T_{YF}' when the gate control for 'T_{YF}' is enabled. 'T_{XF}' is automatically reverse biased, as V_L is now pinned to V_Y, and is turned 'OFF'. No additional commutation circuit is required for this transition.

Case II: $V_Y < V_X$ & $I_L > 0$

Switching in this case would require a forced commutation circuit. 'T_{YF}' is reverse biased and will not "naturally" pick up the load current even if its gate signal is enabled. This case corresponds to an undesirable region for attempting a stator transition in the DFM.

Case III: $V_Y < V_X$ & $I_L < 0$

As the load current is negative, SCRs 'T_{XF}' and 'T_{YF}' are non-functional and their gate control is permanently disabled. Similar to Case I, enabling gate signal of 'T_{YR}' can *naturally commutate* the load current from 'T_{XR}' to 'T_{YR}'. No additional commutation circuit is required for this transition.

Case IV: $V_Y > V_X$ & $I_L < 0$

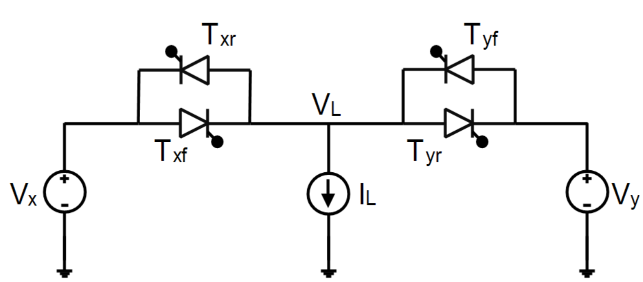


Figure 3. Single cell of a SCR-based transfer switch connected between a constant current load and two arbitrary voltage sources.

Similar to case II, additional *forced commutation* circuit is required to turn 'T_{XR}' OFF and forms an undesirable region for source transition for the DFM.

C. Three-phase SCR-based transfer switch

The single cell analysis can now be extended for a DFM load with three phase source connection. The proposed SCR based three phase transfer switch connected to the stator of the DFM is shown in Fig. 4. One of the sources is dc represented by 'V_{dc}' and the other is a three phase ac represented by 'V_a', 'V_b' and 'V_c'. The rotor is fed from a controlled converter.

1) Transition from dc to ac stator voltage

Assuming that the dc source is connected to the stator of the DFM, implies that SCRs 'T_{adcf}', 'T_{bdcr}' and 'T_{cdcr}' are 'ON' and the current is positive in the A-phase and negative in the B and C phases. The single cell analysis for commutation can be extended to all three phases using the stator A-phase winding axis as reference on a commutation diagram as shown in Fig. 5(a). The dc source voltage magnitude, shown as a dashed line in Fig. 5(a), is relatively small compared to the incoming ac voltage. Before the transition, the stator voltage vector (V_{DC}) and the current vector (I_S) are both stationary, aligned and oriented towards A-phase axis, while ac voltage vector (V_{AC}) is rotating at the ac supply frequency. Since the A-phase current is positive, an ac voltage in the A-phase greater than the dc source voltage will ensure natural commutation of SCR 'T_{adcf}'. This is shown by the red arc in Fig. 5(a). Similarly, the currents in the B-phase and C-phase being negative, any negative ac source voltage in the B and C phases ensures natural commutation of SCRs 'T_{bdcr}' and 'T_{cdcr}' shown by green and blue arc in Fig. 5(a). Sections where all three arcs overlap indicate operating conditions where natural commutation could occur for all three dc-side SCRs simultaneously. As can be seen in the Fig. 5(a), a ±30° region exists where all dc side SCRs undergo natural commutation simultaneously transitioning the stator of the DFM to the ac source.

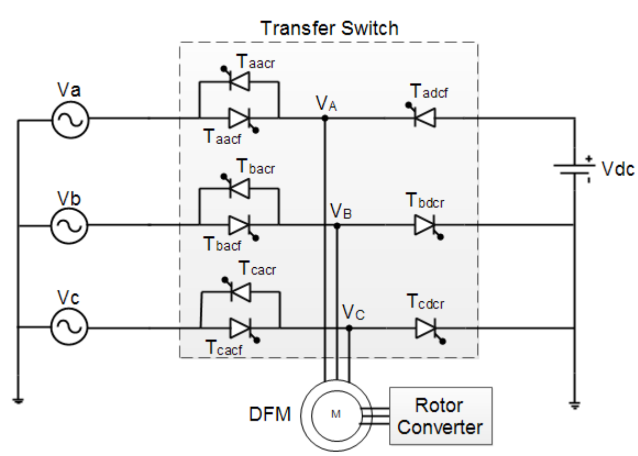


Figure 4. Three-phase SCR-based transfer switch connected to the stator of the DFM.

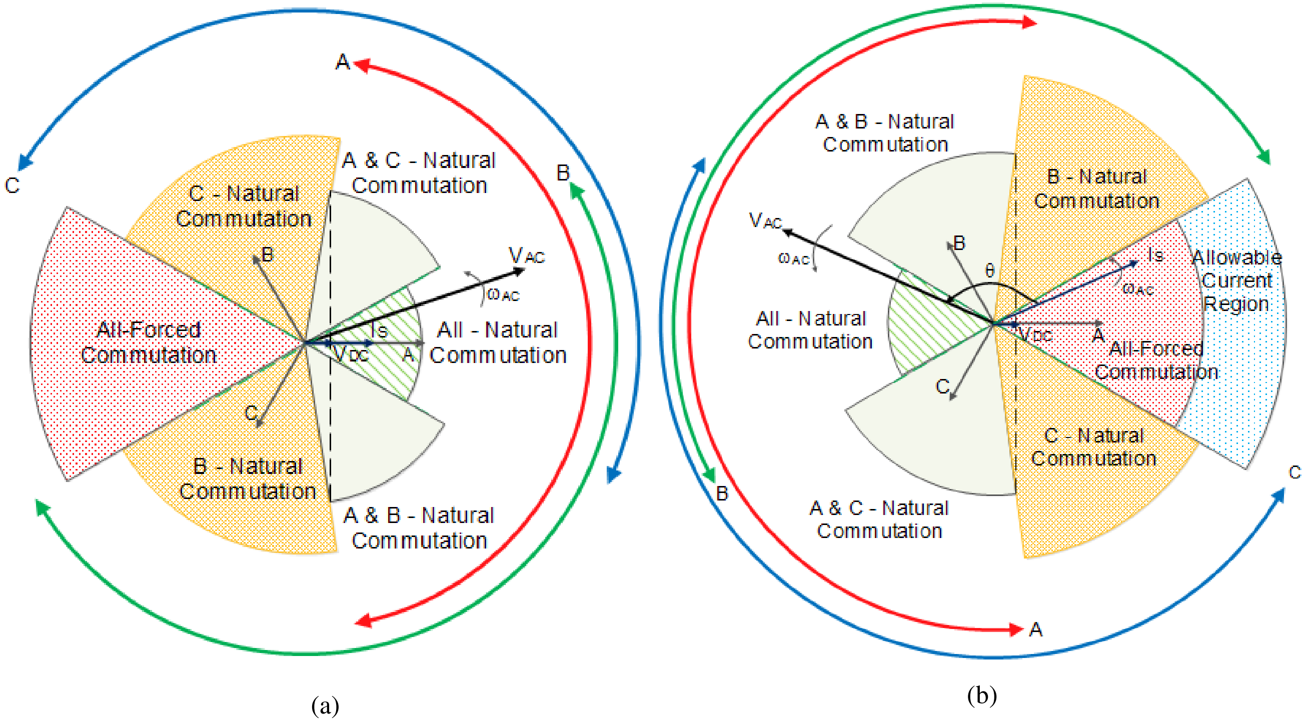


Figure 5. Commutation diagram: (a) Regions of natural and forced commutation of the dc side SCRs during dc-to-ac transition (b) Regions of natural and forced commutation of the ac side SCRs during ac-to-dc transition.

2) Transition from ac to dc stator voltage

On the other hand, when the stator of the DFM is initially connected to the ac source, all ac side SCRs (‘T_{aacf}’, ‘T_{aacr}’ ‘T_{bacf}’, ‘T_{bacr}’ ‘T_{cacf}’ and ‘T_{cacr}’) operate on 180º conduction mode based on the DFM stator current and the ac source voltage polarity. Since the dc side SCRs only allow positive current for the A-phase and negative current for the B and C phases, at the transition instant from ac to dc, natural commutation of the SCRs ‘T_{aacf}’, ‘T_{bacr}’ and ‘T_{cacr}’ are only possible without additional commutation circuits. This implies that the DFM stator current vector (I_s) must be within the ±30º “allowable current region” shown in Fig. 5(b). Using the single cell analysis, the regions of natural commutation for the individual phases SCRs (‘T_{aacf}’, ‘T_{bacr}’ and ‘T_{cacr}’) are identified shown by the red, green and blue arc as before. To ensure all the three phases undergo natural commutation at the same instant, the ac source voltage vector must be within 150º and 210º as shown in Fig. 5(b). The complementary region of natural commutation between the two mode transitions, dc-to-ac and ac-to-dc, is as expected. To satisfy both the requirements on the ac source voltage and on the DFM stator current for simultaneous natural commutation of the ac side SCRs, the stator power factor angle (θ) must be greater than 120º. This implies that the active power must flow back to the ac source during the ac to dc source transition.

IV. Control of DFM Drive with Transfer Switch

The commutation diagrams shown in Fig. 5 indicate that transitions between the stator modes can occur “on-the-fly” without shorting the sources or interrupting the load current. Within the arcs of natural commutation, i.e., with appropriate constraints on the ac source voltages and on the DFM stator current at the instant of transition, a simultaneous natural commutation for all the outgoing SCRs can be ensured.

These constraints for natural commutation must be observed to avoid the need for additional commutation circuitry. However, ensuring a smooth torque production, or mechanically “bumpless” shaft behavior during the transition, is also essential. In this section, the DFM constraints are determined and appropriate rotor power electronics control is utilized to make the transition as smooth as possible while crossing between the low and the high speed operating regions. The effect of mechanical loading on the DFM in determining requirements of natural/forced commutation of the outgoing SCRs is examined.

A. Synchronizer

The DFM is connected to the ac source when the rotor speed is higher than the transition speed. On the other hand, it is connected to the dc source in low speed mode. A mode transition is required as the speed crosses the operating boundary in either direction. This transition must occur at a proper instant when the “incoming” source voltage is as consistent with the current operating state as possible to minimally perturb the stator flux and the electromagnetic torque. The synchronizer module [6] measures the incoming source voltage vector, transforms the measurement to stator flux reference frame and waits for the proper match of the d-axis and the q-axis (leads d-axis by 90º by convention) components to command the transition using ‘Sw’ signal in Fig. 1.

For a dc-to-ac mode transition, the d-axis component of the incoming ac voltage is matched to the existing d-axis voltage from the dc source connection, which ensures minimal flux magnitude perturbation. The synchronizer chooses a transition time when the incoming ac voltage appears with a *positive* q-axis component, permitting the stator flux frequency to transition from zero to a positive finite value. In the case of the ac-to-dc mode transition, the d-axis component of the incoming dc voltage is matched to the existing d-axis voltage from the ac source connection but a *negative* q-axis component of the incoming dc voltage ensures proper transition of stator flux frequency to zero. The required conditions become apparent from examining the DFM machine equations as shown in [6]. Satisfying the synchronizer constraint and the natural commutation region constraint of the "outgoing" SCRs will ensure the least perturbation on the DFM and eliminate requirement of the SCRs forced commutation circuits. For a dc-to-ac mode transition, the existing mechanical loading at the shaft prior to the transition plays a decisive role in determining whether the two constraints can be satisfied simultaneously as will be shown in the next section.

B. *dc-to-ac mode transition with DFM constraints*

In the low-speed dc mode, the rotor d-axis current is used to control the stator flux magnitude while the rotor q-axis current sets the electromagnetic torque [6]. The electromagnetic torque is determined by the stator flux magnitude and the rotor q-axis current:

$$\tau_{dc} = -\frac{2}{3}\frac{P}{2}\frac{M}{L_s}\psi_{sdc} I_{rq} \qquad (1)$$

The rotor q-axis current can be expressed in terms of the stator q-axis current and the machine parameters, yielding a torque expression,

$$\tau_{dc} = \frac{2}{3}\frac{P}{2}\psi_{sdc} I_{sq} \qquad (2)$$

Figure 6 shows the stator voltage vector 'V_{DC}', stator current vector 'I_S,' and the stator flux vector 'Ψ_{sdc}', all of which are stationary relative to the DFM stator axis in the low-speed dc mode. Since the angle 'δ', shown in Fig. 6, is the angle between the stator flux vector and the stator voltage vector, (2) is represented as,

$$\tau_{dc} = \frac{2}{3}\frac{P}{2}\psi_{sdc} |I_s| \sin\delta \qquad (3)$$

Considering the mechanical load at the shaft to be sufficiently high implies angle 'δ' to be large. Under this condition, if a transition to ac mode is desired, the synchronizer chooses an instant within the arc of natural commutation when the "incoming" ac voltage vector V_{AC} exhibits a d-axis component that matches the existing d-axis stator voltage. This precise instant is illustrated in Fig. 6. As the V_{AC} is within the arc of natural commutation for all three phases, a dc to ac mode transition can be ensured with the least perturbation to the DFM and with all the dc side SCRs undergoing natural commutation.

However, under light load condition, natural commutation in all three phases may not be guaranteed. This situation is

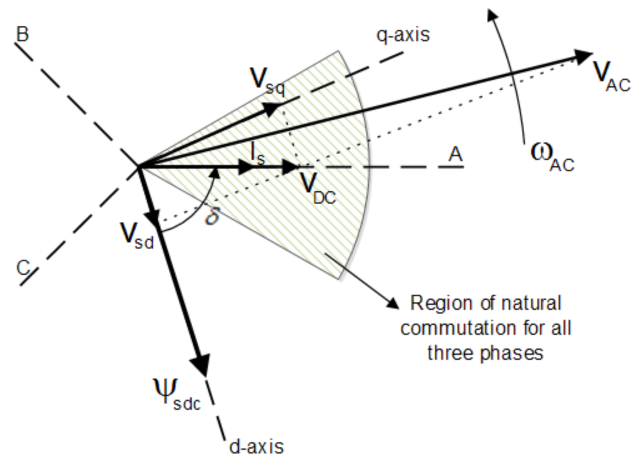


Figure 6. Natural commutation of all the three phase dc side SCRs during dc mode to ac mode transition under heavy load along with least perturbation to DFM.

illustrated in Fig. 7. The angle 'δ' is relatively small under light load. In this case, the synchronizer may not find an instant within the arc of natural commutation which also matches the d-axis component of the "incoming" ac source voltage to that of existing d-axis component of the stator voltage.

Fortunately, in the light load case, the rotor power electronics are lightly loaded, and have plenty of capability to modulate d-axis rotor current to damp the stator flux transient. Hence, the synchronizer, in light load conditions, chooses the best or "last possible" instant to make the transition, at V'_{AC} in Fig. 7, when natural commutation for all outgoing dc side SCRs are still possible. A stator flux transient occurs, which is damped by a full-state feedback controller that minimizes the stator flux oscillation [5].

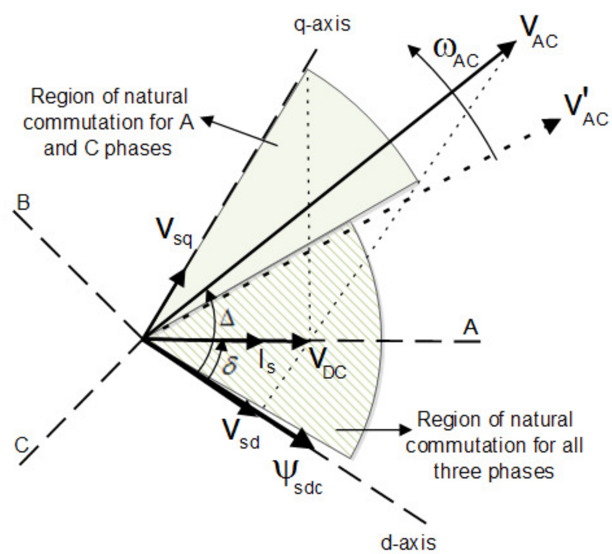


Figure 7. Guaranteed natural commutation of the A and C phases SCRs under light load condition. Transitioning at V'_{AC} ensures natural commutation of the B phase SCR also but with increased stator flux perturbation.

The boundary that defines what constitutes a light load is determined by the chosen operating stator flux magnitude in the dc mode and the dc and ac source voltages. The boundary condition which can be termed as "light load" occurs when the synchronizer finds V_{AC} exactly on the edge of the arc of natural commutation for all the three phases at the instant when the d-axis component of the source voltages match i.e. from the geometry exposed in Fig. 7,

$$V_{sd} = |V_{DC}|\cos\delta_{\min} = |V_{AC}|\cos\Delta \quad \text{and} \quad \Delta - \delta_{\min} = \frac{\pi}{6} \tag{4}$$

Solving (4), the boundary of "light load" is given by the minimum 'δ':

$$\delta_{\min} = \tan^{-1}\left(\sqrt{3} - 2\frac{|V_{DC}|}{|V_{AC}|}\right) \tag{5}$$

The minimum torque below which the load is termed as "light" is, therefore, given using (3) and (5) as,

$$\tau_{dc,\min} = \frac{2}{3}\frac{P}{2}\psi_{sdc}\frac{|V_{DC}|}{R_s}\sin\left[\tan^{-1}\left(\sqrt{3} - \frac{2|V_{DC}|}{|V_{AC}|}\right)\right] \tag{6}$$

C. ac-to-dc mode transition with DFM constraints

The two major differences in the high speed ac mode of operation of the DFM compared to that of dc mode operation are, first, the angle between the stator voltage and the stator flux is relatively fixed and is close to 90º independent of the mechanical load (assuming low stator resistance). Second, the stator voltage 'V_{AC}', the stator current 'I_S' and the stator flux 'Ψ_{sac}' vectors rotate at ac supply frequency along with the d-q reference frame w.r.t stationary dc source voltage vector 'V_{DC}' and stator 'ABC' winding axis. The rotor power electronics control is required to assist a smooth transition from the ac to dc mode with natural commutations of ac side SCRs.

The requirement of reverse power flow in the stator of the DFM for natural commutation of the ac side SCRs is inherently achieved by the nature of the proposed DFM drive. While braking or slowing the machine to the low-speed or dc-mode operating regime, the stator power is automatically reversed using the rotor power electronics. The power factor angle of the stator is actively controlled using the rotor power electronics during the braking operation by command of d-axis rotor current. The synchronizer matches the d-axis components of the source voltages and ensures a negative q-axis component of the "incoming" dc source voltage. Figure 8 shows the precise instant when all the requirements based on the natural commutation and smooth mode transfer is achieved.

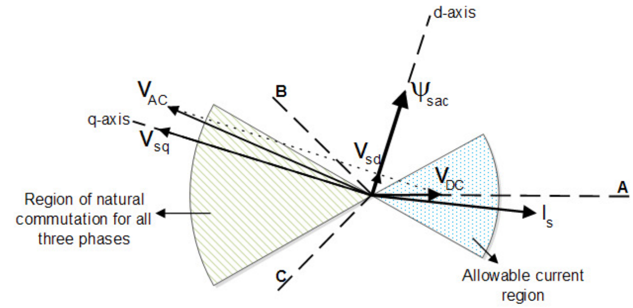


Figure 8. Natural commutation of ac side SCRs 'T_{aacr}', 'T_{bacr}' and 'T_{cacr}' during ac mode to dc mode transition with proper reactive power control and braking using rotor side converter.

V. Experimental Results

A 1 HP, 220 V/ 150 V, 60 Hz, 4 Pole DFM has been used to illustrate the proposed DFM drive. Two Texas Instruments High Voltage Motor Control & PFC Developer's Kits, named Kit-I and Kit-II and a separate dc source are used for the demonstration. Kit-I is programmed to operate as an ac source of 60 V (phase peak), 20 Hz. An output LC filter is used to filter the harmonics of Kit-I and generate sinusoidal ac voltages. The dc source is Agilent 20V dc supply. The DFM is also mechanically coupled to a Permanent Magnet Synchronous Generator (PMSG) which is connected to a programmable load bank. To evaluate the proposed switching, the SCR based transfer switch as shown in Fig. 4 is built using IXYS-cs22-08IO1M thyristors. An RC snubber (330 ohms and 6.8 nF) is connected in parallel with the SCRs to limit the dv/dt stress. The parameters of the DFM is shown in Table. I.

TABLE I. DFM Parameters

Stator resistance	3.575 Ω
Rotor resistance	4.229 Ω
Stator leakage inductance	9.6 mH
Rotor leakage inductance	9.6 mH
Mutual inductance	165 mH
Moment of inertia	0.01 kgm^2
Frictional coefficient	0.0025 Nm-s/rad

A. Experimental results: dc-to-ac transition

The transition from the dc to the ac mode for the DFM drive is evaluated under different loading conditions. First, a step of 900 rpm is commanded in the reference speed. This case corresponds to high load condition as the DFM produces rated torque while accelerating through the transition speed. Second, a ramp with a slope of 112.5 rpm/s is commanded for 8 seconds. With lower requirement on the acceleration torque, this case corresponds to light load while transitioning from the dc-to-ac mode. The ac supply synchronous speed is 600 rpm while the transition speed is set as 360 rpm. Figure 9 shows the result under the two loading conditions. The speed response shown in Fig. 9(a) is as expected under the step and ramp reference command. The dc-to-ac mode transition occurs as the speed crosses the transition speed of 360 rpm. No uncontrolled speed variation is observed during the transition. The electromagnetic torque produced by the DFM remains smooth during the mode transition as shown in Fig. 9 (b). The DFM stator current is shown in Fig. 9 (c) where initially the current is dc in nature, which changes to ac at the mode transition. The A-phase stator current is plotted in Fig. 9 (d) along with the dc side and the ac side SCR currents in micro-second time scale to show the current commutation during mode transition. In this small time scale, the load current behaves like a constant current load. The dc side SCR commutates and the load current is transitioned to ac side SCR

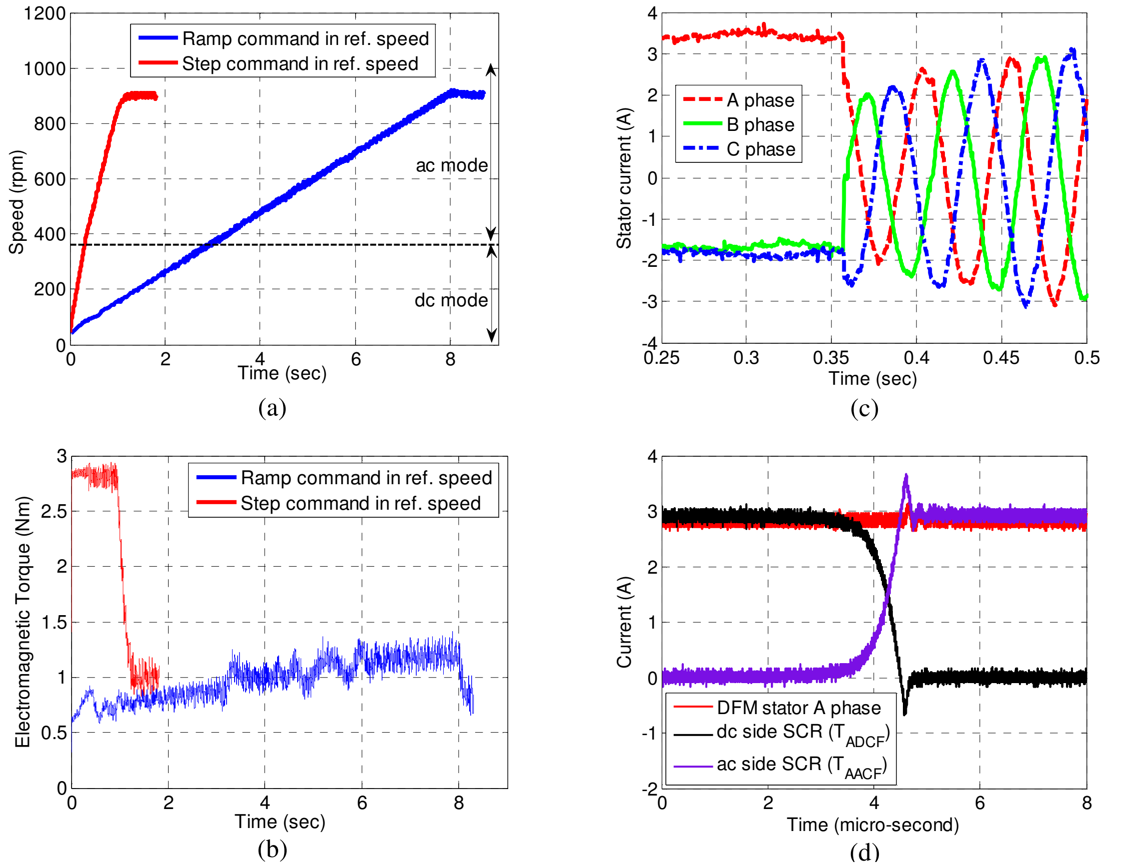


Figure 9. Experimental Results: dc-to-ac mode transition with SCR based transfer switch connected to the stator. (a) Speed response of the drive under step and ramp reference speed command; dc mode to ac mode transition happens when the speed crosses 360 rpm (b) Electromagnetic torque during the step and ramp command in reference speed. (c) Three phase DFM stator currents changes from dc-to-ac at the mode transition simultaneously (d) With the DFM stator A-phase current remaining unperturbed during the transition, the dc side SCR (T_{adcf}) current commutates to ac side SCR (T_{aacf}) in micro-second time scale.

without interruption. Figure 10 (top) shows the effect the dc-to-ac transition under light load conditions on the stator flux magnitude without stator flux damping. With an active stator flux transition controller [5], controlled rotor d-axis current within the limits of the DFM and the rotor power electronics current rating, damps the oscillation as shown in Fig. 10 (bottom).

B. *Experimental results: ac-to-dc transition*

To perform an ac-to-dc mode transition, a step command of zero speed is set as reference while initially the DFM drive is running at 900 rpm. The speed response is shown in Fig. 11 (a). The ac-to-dc mode transition occurs when the speed drops below the transition speed of 360 rpm. The source voltages and the stator currents are shown in Fig. 11 (b) and (c). The power reversal to the ac source during braking is seen based on the phase angle between the ac source voltage and the stator current before the transition. After the transition, the B-phase current gradually drops to zero due to transient effect and remains zero for 10 ms as the dc side SCR does not allow current to sink to the dc source. However, this does not impact the speed. Reactive power control along with reverse power

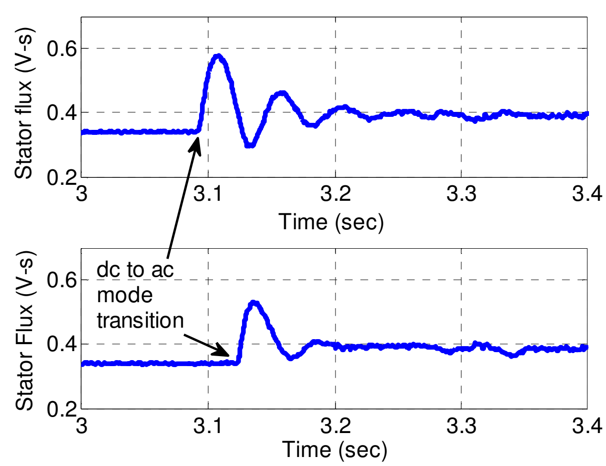
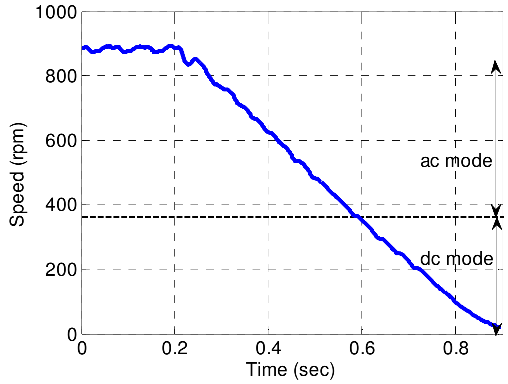
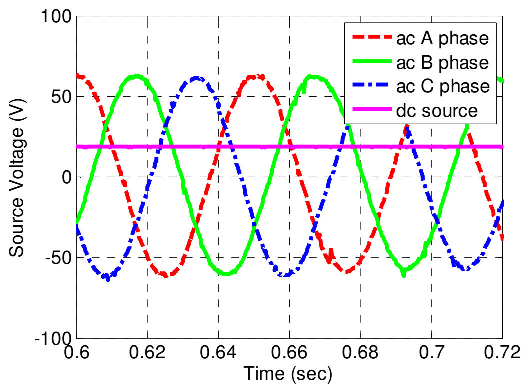


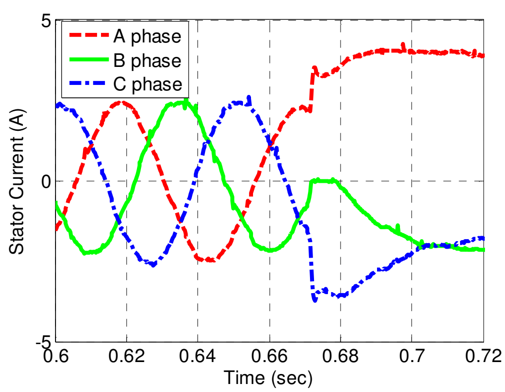
Figure 10. Effect on the stator flux magnitude due to light load dc-to-ac mode transition. Top: Without stator flux transition controller. Bottom: Damped oscillation with active rotor d-axis current control commanded by stator flux transition controller.



(a)



(b)



(c)

Figure 11. Experimental results: ac-to-dc transition with a step command in reference speed to zero. (a) Speed response of the DFM drive without any uncontrolled speed region during transition. (b) ac and dc source voltages (c) Stator current of the DFM undergoes ac-to-dc transition below transition speed.

flow in the stator allows natural commutation of the ac side SCRs.

VI. Conclusion

This paper presented and demonstrated a SCR based static transfer switch that can change stator supply between an ac and a dc source on-the-fly for a DFM drive suitable for high power VSD. Rotor current control not only allows "bumpless" transition between modes, but also enables reduction of SCR commutation circuits by controlling the phase angle between the stator voltage and the stator current during the transition. Usage of SCRs to form up the stator switch while allowing instantaneous transition without shorting of sources or impairing load currents helps in significant reduction of controlled power electronics and associated auxiliaries. With the availability of high power SCRs and utilizing their short time current ratings, a hybrid transfer switch can be devised to reduce power electronics requirement for high power drives even to a greater extent.

Acknowledgement

This research was performed with support from the Electric Ship Research and Development Consortium under The Office of Naval Research. This work was also in part supported by The Grainger Foundation and the MIT EECS SuperUROP program.

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