Optimal Reference Frame Angle Approach for Air-gap Flux Minimization in Dual Stator Winding Induction Machines

M. Ayaz Khoshhava, H. Abootorabi Zarchi[1], G.R. Arab Markadeh[2]

***Abstract*—Dual Stator Winding Induction Machines (DSWIMs) which have two sets of three phase windings with unequal pole pairs in their stator and a standard squirrel cage rotor, have overcame the narrow speed operation region and circulating current problems exists in other types of dual winding machines. These advantages are resulted from the independent operation of their winding sets. The independent operation of winding sets will be guaranteed if the flux saturation is avoided. This paper proposes a novel reference frame angel determination technique which not only guarantees the flux saturation avoidance but also results in flux optimization in DSWIMs. Despite the pervious methods, the proposed method doesn't require position or speed sensor and it is easily applicable in various control schemes and in different reference frames. This method is implemented in a flux and torque vector control system for driving a 3.3kW DSWIM. The experimental results confirm the effectiveness of the proposed method. Moreover, by implementing the proposed method, the torque sharing between two winding sets is properly done according to the power rating of each of them.**

***Index Terms*—Dual Stator Winding Induction Machines (DSWIMs), optimal reference frame angle, Air-gap flux minimization.**

I. Introduction

RECENTLY the interest in dual winding machines for various applications is growing, since these machines have some advantages over single winding machines such as enhanced reliability, higher flexibility and increased power rating. From one viewpoint, there are two main groups of dual winding machines: split-wound and self-cascaded [1]. In the first group, the stator contains two sets of shifted three phase windings wounded for the same number of pole pairs. This configuration has been first introduced for improving the reliability and the power rating of synchronous generators [1]. Indeed, utilizing two winding sets allows for power sharing between two power converters. Thus, converter power limitation problem is overcame. Pertaining these advantages has made split-wound machines as a good candidate for various applications such as electric vehicles, aircrafts and ship propulsion systems [2-4]. However, implementing similar pole pairs arrangement results in direct coupling among winding sets. Consequently, slight voltage unbalance could result in high circulating currents. The second category of dual winding machines (self-cascaded) which are known as Brushless Doubly Fed Machines (BDFMs), were first introduced in 1907 [5]. BDFMs have two sets of three phase windings with dissimilar pole pairs in their stator and their rotor has a special structure called nested loop. These machines have solved the direct coupling problem exists in the split-wound machines and they have been applied in different motoring and generating systems, especially for narrow speed applications. Nevertheless, their construction costs are high and they are inapplicable for systems operating in a wide speed range [6].

In 1998 a new type of dual winding induction machine has been introduced by Lipo et al. [7]. The stator of these machines (called Dual Stator Winding Induction Machines (DSWIMs)) has a similar structure to BDFMs, however their rotor is a standard squirrel cage one. In spite of BDFMs, DSWIMs can operate in a wide speed region including zero speed. Moreover, utilization of standard squirrel cage rotor has significantly decreased their fabrication cost in comparison to BDFMs. It is proved in [8] that this structure cancels any direct and indirect coupling among winding sets. This condition is guaranteed if the windings are wound for different number of poles and also the air-gap flux saturation is shunned. Indeed, saturation in DSWIMs results in high order inter-winding torques and degrades the control performance [8]. Consequently, the magnetic saturation should be avoided by keeping the total air-gap flux under a permissible level. Since, the DSWIM advantages over other sorts of induction machines are based on the independent operation of winding sets.

The total air-gap flux density in a DSWIM is sum of the flux density vectors produced by each of the winding sets. Therefore, it depends on not only the flux density magnitude produced by each winding set, but also their relative positions. Let's consider the air-gap flux density produced by each winding set to be a sinusoidal waveform. The best possible case for total flux density minimization is achieved when the maximum point of one of the waveforms is occurred at the minimum point of the other one. On the contrary, the worst possible case is achieved when both maximum points are occurred simultaneously. Based upon these two cases, two strategies are adopted to prevent flux saturation in DSWIMs:

1) *Assuming the worst possible case:* in this strategy the individual winding flux magnitude is limited such that the maximum total flux be under a permissible level. This strategy which is proposed in [8], is easy to implement. However, it does not result in air-gap flux optimization.
2) *Assuming the best possible case:* in this strategy the

[1] M. Ayaz Khoshhava and H. Abootorabi Zarchi are with Department of Engineering, Ferdowsi university of Mashhad. (Email: mojtaba.ayaz@mail.um.ac.ir; abootorabi@um.ac.ir)
[2] G. Arab Markadeh is with Department of Engineering, Shahrekord University. (Email: arab-gh@eng.sku.ac.ir)

winding fluxes should be synchronized and their relative position must be controlled to minimize the total flux.

The second strategy is realized in [9-12] through torque sharing in the rotor flux reference frame. The proposed method implementation is complicated. Moreover, it may result in overload in winding sets. Since, the torque sharing is fulfilled to guarantee the optimal relative flux position and not based on the winding power ratings. Additionally, it cannot be implemented in sensor-less applications.

In this paper a novel method is proposed for the second strategy realization. The proposed method which is based on optimal reference frame angle selection, overcomes the discussed limitations in the previous methods. The proposed strategy which is pertinent to various vector control schemes, possesses significant advantages over previous methods that can be addressed as follows:

1- Despite the first approach this method minimizes the total air-gap flux and thus results in optimal DSWIM iron utilization. While, similar to the first approach, its implementation is not complicated.

2- This method is free of position or speed sensor. Consequently, it can be adapted in various sensor-less DSWIM drive schemes.

3- In contrast to the second approach, the proposed strategy realization doesn't involve torque sharing. As a result, the torque can be shared independently and based on the winding power ratings.

II. The Proposed Flux minimization Method

Considering the flux produced by each winding set to be sinusoidal and synchronized. The total air-gap flux density equals:

$$B_{gt} = B_{g1}\cos(\frac{p_1}{2}\theta_{mech}) + B_{g2}\cos(\frac{p_2}{2}(\theta_{mech} - \theta_{shift}) + \delta) \tag{1}$$

Where, B_{gt}, B_{g1} and B_{g2} are the amplitude of the total air-gap flux density and the flux densities produced by *ABC* and *XYZ* winding sets, respectively. p_1 and p_2 are the number of pole pairs of ABC and XYZ winding sets, respectively and θ_{mech} stands for the stator position measured from one pole of *ABC* winding set. The angular distance between reference poles of *ABC* and the closest pole of *XYZ* winding set is shown by θ_{shift} and δ represents the relative position between the flux densities of *ABC* and *XYZ* winding sets.

As previously stated, the total air-gap flux density is minimized if the maximum flux density of one of the winding sets occurs while the other is at its reverse maximum point. Accordingly, the optimal condition will be as follows:

$$\frac{p_1}{2}\theta_{mech} = \pm\pi \tag{2}$$

$$\frac{p_2}{2}(\theta_{mech} - \theta_{shift}) + \delta = 0 \tag{3}$$

Calculating θ_{mech} from (2) and substituting it in (3) results in:

$$\delta_{optimal} = \frac{p_2}{2}\theta_{shift} \mp \frac{p_2}{p_1}\pi \tag{4}$$

Figure 1 illustrates the total air-gap flux density for a DSWIM **with** $\theta_{shift} = 0$ **for various** pole pairs ratios. As it is clear, for a DWSIM with unequal pole pairs, the optimal pole pairs ratio and $\delta_{optimal}$ are 3 and 180°, respectively.

Based on the above discussions, the air-gap flux minimization is achieved if two circumstances are assured:

1) The synchronization of fluxes produced by the two winding sets.

2) Their relative position to be as stated in (4).

In this paper these two circumstances are guaranteed through optimal reference frame angle determination in a vector controlled scheme. The block diagram of the proposed optimal reference frame angle determination strategy is depicted in Fig.2. In order to assure the first condition, the frequency of the winding fluxes should have a ratio equal to the ratio of the pole pairs. Accordingly, in the first step of the proposed strategy, the reference frame angle of the *ABC* winding set is multiplied by the pole pairs ratio. In this way, a reference frame angle is determined for the *XYZ* winding set which guarantees the flux synchronization. This angle is represented by $\theta_{synchron}$ in Fig. 2. In the second step equation (4) is guaranteed by an angle regulator which is a Proportional Integral (PI) controller. This regulator outputs a correction angle ($\theta_{correct}$) which is added to the reference frame angle determined in the first step.

$$\theta_2 = \theta_{synchron} + \theta_{correct} \tag{5}$$

Although, this strategy is applicable for various vector control schemes and in any arbitrary reference frame, in the following it is applied in a vector control system in the stator flux reference frame.

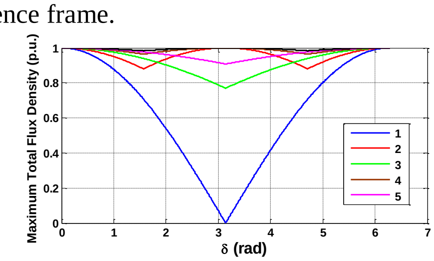


Fig. 1. The maximum value of the total flux density for various pole pairs ratios

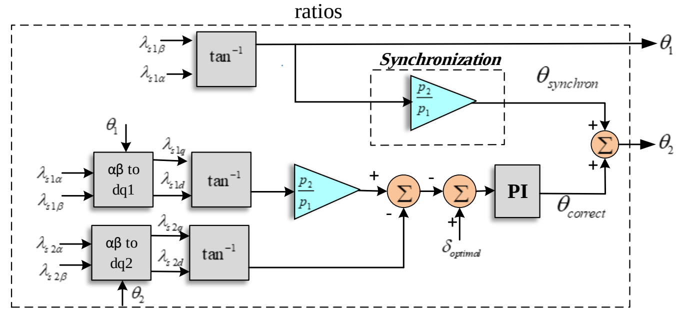


Fig. 2. Optimal reference frame angle calculation

III. Proposed Control System

The proposed flux minimization method is implemented in a Field Oriented Control (FOC) system in the stator flux reference frame which controls the total electromagnetic torque and winding fluxes of a DSWIM. The block-diagram of this control system is illustrated in Fig. 3. As it is shown, in this system the measured winding currents and voltages are transferred to αβ form via the Clark Transformation. Based on the transferred variables the winding fluxes are calculated.

After that, according to the calculated winding fluxes the optimal reference angles are determined (utilizing the method discussed in the previous section). These angles which are determined without position sensor requirement, are adapted to transform the three phase measured currents to the two axis currents. In the proposed control system the reference electromagnetic torque is shared between two winding sets dependent on the torque partitioning factors (*k* and *1-k*), which are determined based on the power ratings of winding sets. This prevents the overloading of winding sets in all operation conditions. The produced electromagnetic torque of each winding set is compared to its reference value and the resulting errors are passed through related PI controllers. The outputs of these PI controllers produce the reference q-axis currents. The q-axis currents errors are also passed through their associated PI controllers. This way, the q-axis reference voltages are produced for the Voltage Source Inverters (VSIs). A similar procedure is fulfilled for the d-axis reference voltage generation, except that the d-axis reference current is determined based on the flux magnitude deviations from their reference values.

IV. EXPERIMENTAL RESULTS

The proposed control system is employed to drive a 3.3kW DSWIM through a DSP-based test bench depicted in Fig. 4. The DSWIM is an in-lab made machine and its nominal parameters and frame parameters are tabulated in table I and II, respectively. According to the power rating of *ABC* and *XYZ* winding sets, *k* and *1-k* are selected to be 0.85 and 0.15, respectively. As illustrated in Fig. 4 the modular drive system comprises two VSIs supplying the *ABC* and *XYZ* winding sets. The switching frequency for VSIs is 10 kHz. In the experimental test bench the line currents are measured via two current sensor boards including LEM LA55P current sensors. Moreover, the line voltages are sampled through a voltage sensor board containing four LEM LV-25-P voltage sensors. In addition, it is provided an analog second-order low pass filter with 2.6 kHz cut-off frequency to filter the output of the current and voltage sensor boards. All control commands in the drive system are issued by the TMS320F28335 signal processor board designed by Texas Instrument Co. As depicted in Fig.4 the DSWIM provides the mechanical power for a DC generator supplying a resistive load. The experimental tests are performed under full load condition and the DSWIM mechanical load is 11.15 N.m. Figures 5 to 7 illustrate the experimental results obtained through the test bench depicted in Fig. 4.

Figure 5 illustrates the relative position angle between the fluxes produced by *ABC* and *XYZ* winding sets ($\Delta\Theta$) calculated at *XYZ* reference frame. As it is clear the $\Delta\Theta$ is rapidly controlled at its optimal value (180°). According to Fig.1 this relative position angle guarantees the optimal flux condition during the control process.

Figure 6 shows the amplitude of the flux produced by *ABC* and *XYZ* winding sets and their reference value (which are their nominal fluxes). As depicted, the flux controllers can properly fix the winding fluxes at their reference values.

The *ABC* and *XYZ* windings electromagnetic torque and their reference values are depicted in Fig. 7 (a) and (b), respectively. As illustrated, the *ABC* winding set produces approximately 9.47 N.m. electromagnetic torque which is 85% of the required torque. Similarly, the *XYZ* winding set produced torque is fixed at its nominal value (1.67 N.m.) and this winding supplies 15% of the required electromagnetic load.

In conclusion, by implementing the proposed control system the required electromagnetic torque is shared between two winding sets according to their nominal ratings and no over-load condition occurred for two winding sets during the control process. Moreover, the winding fluxes are properly fixed at their nominal values and as the relative position angle is kept at its optimal value in the whole control process, the DSWIM can output its nominal power free of flux saturation.

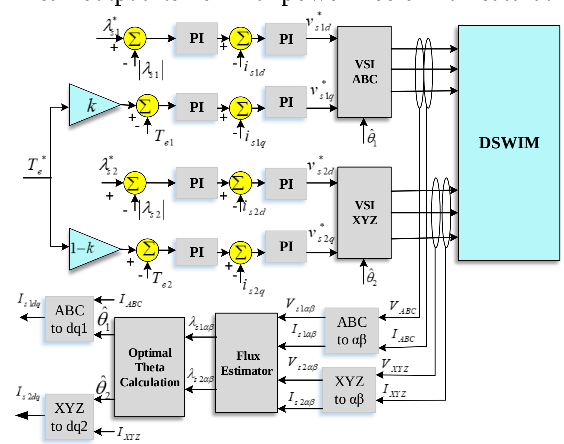


Fig. 3. Proposed DSWIM control system

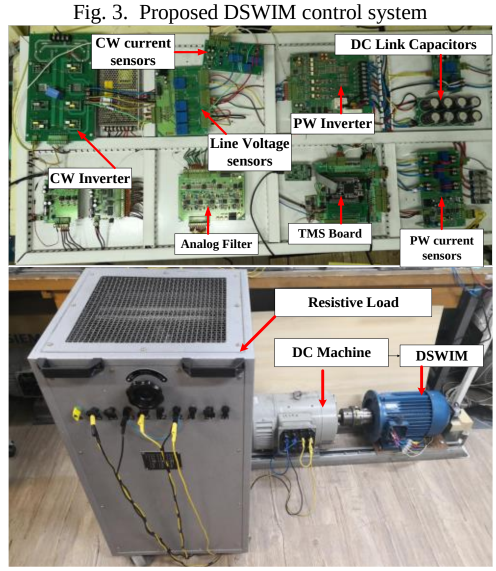


Fig.4. Experimental test setup

TABLE I
DSWIM Nominal Parameters

Parameter	Value	
	ABC	*XYZ*
Pole number	2	6
Output Power	2830W	500W
Voltage Frequency	50 Hz	150 Hz
RMS Line Voltage	230 V	80 V
Phase Current	9A	5 A
Rotor Speed	2850 rpm	
Efficiency	88%	
Nominal Torque	11.15N.m	

TABLE II
DSWIM Frame parameters

Stator Parameters		Rotor Parameters	
Parameters	**Value**	**Parameters**	**Value**
Internal diameter	104.8982 mm	Internal diameter	104.2508 mm
External diameter	167.0156 mm	Air-gap length	0.3241 mm
Core length	139.0014m	Core length	141.7015 mm
Slot area	89.0112 mm^2	Slot area	59.1021mm^2
Slot depth	15.5391 mm	Slot depth	16.7502 mm
Number of slots	36	Number of slots	28
Tooth width	6.9012 mm	Tooth width	10.1901 mm
Winding number of turns	96	Winding number of turns	96

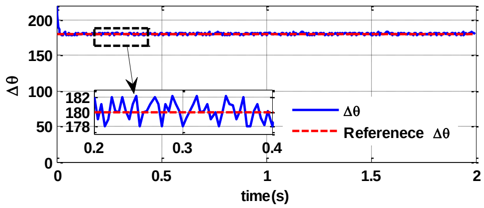
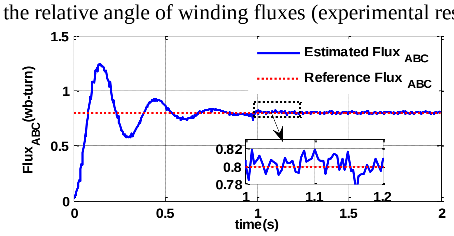
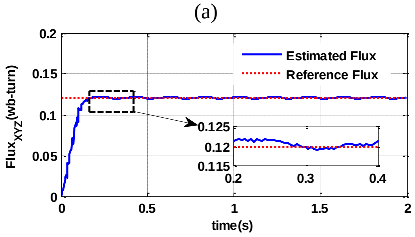


Fig.5. the relative angle of winding fluxes (experimental result)



(a)

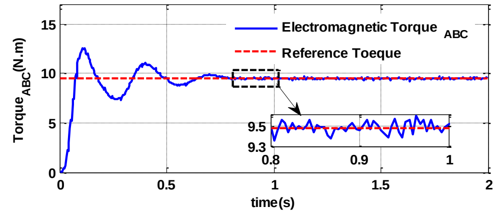


(b)

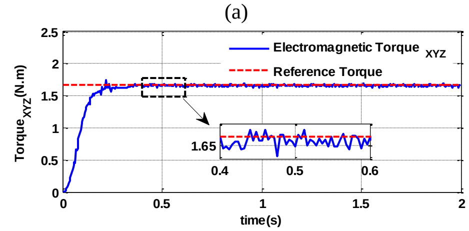
Fig.6. Stator Flux a) *ABC* winding set b) *XYZ* winding set (experimental result)

V. Conclusion

An innovative reference frame angel determination method was introduced for DSWIM control systems. This method made it possible the optimal utilization of the DSWIM iron. The proposed method was applicable in various vector control schemes and reference frames without any position or speed sensor necessity. This method was applied in a DSWIM vector control system for controlling the winding fluxes and their electromagnetic torques. The experimental results illustrated that implementing the proposed technique assures the synchronization of winding fluxes and also their optimal relative positions. Moreover, the winding fluxes properly followed their reference values. Similarly, the winding electromagnetic torques were suitably fixed at their commands determined based on their power ratings and DSWIM total reference torque.



(a)



(b)

Fig.7. Electromagnetic Torque a) *ABC* winding set b) *XYZ* winding set (experimental result)

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