A new optimal DTC switching strategy for open-end windings induction machine using a dual-inverter

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ABSTRACT

Early in 1980s, fast torque dynamic control has been a subject of research in AC drives. To achieve superior torque dynamic control, two major techniques are used, namely field oriented control (FOC) and direct torque control (DTC), spurred on by rapid advances in embedded computing systems. Both approaches employ the space vector modulation (SVM) technique to perform the voltage source inverter into over modulation region for producing the fastest torque dynamic response. However, the motor current tends to increase beyond its limit (which can damage the power switches) during the torque dynamic condition, due to inappropriate flux level (i.e., at rated stator flux). The proposed research aims to formulate an optimal switching modulator and produce the fastest torque dynamic response. In formulating the optimal switching modulator, the effects of selecting different voltage vectors on torque dynamic responses will be investigated. With greater number of voltage vectors offered in dual inverters, the identification of the most optimal voltage vectors for producing the fastest torque dynamic responses will be carried out based on the investigation. The main benefit of the proposed strategy is that it provides superior fast torque dynamic response which is the main requirements for many alternating current (AC) drive applications, e.g., traction drives, electric transportations and vehicles.

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1. INTRODUCTION

Low and medium-power applications are typically served by induction motor drives. Researchers have modified the power and control circuit designs of this motor to make it suitable for higher-power applications [1]. Open-end winding is one of the modifications, three-phase stator windings with two separate inverters. The direct torque control (DTC) scheme for induction motor drives has gotten a lot of attention in recent years in automotive motor drive applications [2]. The reasons of its popularity are due to its simple structure and fast torque dynamic response, as compared with the field-oriented control (FOC) scheme [3], which was introduced a decade earlier. Hasse proposed the notion of indirect field oriented control (IFOC) in 1968 [4], [5]. Blaschke later developed direct field oriented control (DFOC) within Siemens in 1971. Both authors suggested a rotor flux vector-aligned orientation. In 1979, a vector-controlled AC drive developed by Toshiba in the industry, which consisted of an inverter and an induction motor. Werner Leonhard of the

Technische Universitat Braunschweig further developed FOC methods in 1980, expanding more opportunities for AC drive. In [6] SVM-DTC was implemented and it maintains constant switching frequency irrespective of rotor speed. To reduce torque and flux ripples further research has been carried on SVM-DTC [7]-[9]

The motor equations are turned (rewritten) in FOC into a coordinate system that rotates in lockstep with the rotor flux vector. Under constant rotor flux amplitude, there is a linear relationship between control variables and torque in the field coordinate system. The decoupled torque production in an individually excited DC motor corresponds to this transformation, which has a good physical basis. However, from a theoretical standpoint, field orientation is not limited to rotor flux orientation, but may also include stator or air gap flux [10]. There were a few references in the late 1980 s on stator flux orientation [11] that showed some benefits over rotor flux-oriented control. The universal field orientation theory is a generalization [12].

When it emerged in the mid-1980s that control systems would be standardized based on the FOC philosophy, Depenbrock [13], [14], and Takahashi and Noguchi published groundbreaking research departing from the concept of coordinate transformation and comparison with DC motor control. Depenbrock suggested direct self-control (Direkte Selbstregelung) in 1986 (while at Brown Boveri, now ABB), primarily for high-power drives with voltage source inverters. Takahashi and Noguchi (1986) suggested direct torque control, which was designed primarily for low, and medium voltage drives. These pioneers recommended replacing motor decoupling with bang-bang self-control, which works well with inverter semiconductor power devices' on-off operation. Direct torque control (DTC) is the general name for this control approach. Uwe Baader investigated the DTC concept in greater depth and contributed significantly [15].

Unlike FOC, which uses stator current as an inner control goal, direct self-control (DSC) and DTC use hysteresis controls to regulate stator flux. DSC was created with high power and traction in mind. The stator voltage vectors in DTC are chosen directly from the comparative effects of the motor torque and flux with their reference values [16]. In comparison to FOC, both have high torque dynamics. Both control methods, however, have the disadvantages of variable switching frequency and greater torque ripple. Since then, researchers have been working tirelessly to overcome these innate flaws. These issues provided researchers with numerous opportunities to work on various strategies to prevent the variable switching frequency [17]-[19], while remaining true to the basic principle of torque control.

A hysteresis comparator controls the torque and flux linkage in a typical DTC, and a switching table chooses the voltage vector [20]. The conventional two-level VSI fed winding induction motor drive offers only eight voltage vectors (six active voltage vectors and two zero voltage vectors), and the selection of the vector is not exactly the most suitable vector for the performances of DTC. Alternatively, implemented DTC in dual inverter for open end winding gives the greater number of vectors where more freedom to select the most optimal voltage vector which gives the best performances. However, the selection of active vectors to regulate the stator flux into a circular flux path during a torque dynamic condition, does not guarantee to produce the fastest torque dynamic responses. This is due to the fact that one of two active voltage vectors used to control the flux is not the optimal vector that can provide a quick stator flux change and hence a fast torque dynamic response. Therefore, the propose method by using open-end winding with dual-inverter is presented to improve the torque dynamic response. This article is structured is being as. Section 2 discussed on conventional method by using single-sided supply and open-end winding induction machine while in section 3 presents on the simulation results for both methods discussed on section 2.

2. SINGLE-SIDED SUPPLY AND OPEN-END WINDING INDUCTION MACHINE

2.1. Single-sided supply induction machine

The most common single-sided supply setup for induction machines is a two-level VSI connected to the stator winding with a star or delta connection. Figure 1 depicts a typical induction machine setup with a DC source magnitude (Vdc). Figure 2 depicts the VSI switching states that result in eight voltage vectors [21]. The two groups of voltage vectors that can be found are active voltage vectors (V1-V6) and non-active or zero voltage vectors (V0 and V7). The six active voltage vectors have the same magnitude but with different angle. When there is a single magnitude to control the torque or/and flux at the same rate of rise, the DTC has only one choice. However, at extreme operating conditions (e.g., at very low speeds), the vector selection appears to be insufficient, resulting in high switching frequencies and torque ripple.

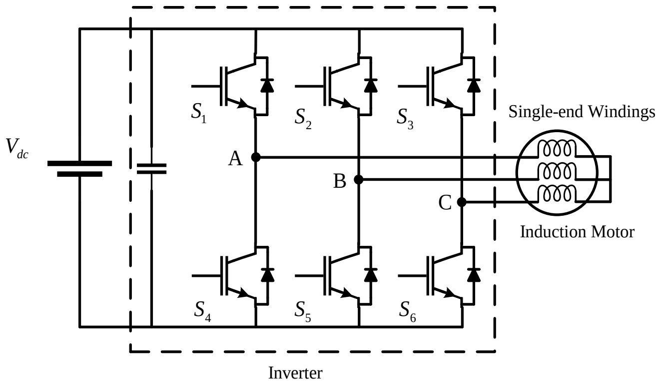

Figure 1. The single-sided supply induction machine

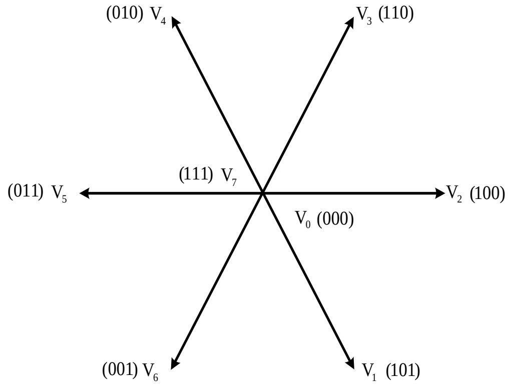

Figure 2. Voltage vector for single-sided winding

2.2. Open-end winding induction machine

Figure 3 depicts a schematic of the induction motor drive's open-end winding configuration. In this method, two two-level inverters are used to feed power from both sides of the stator windings. The inverter's DC source is set to half the DC voltage of a standard single-sided two-level VSI. Besides, the VSIs' DC sources are electrically separated from one another to prevent the presence of zero-sequence voltage (common-mode voltages) [22].

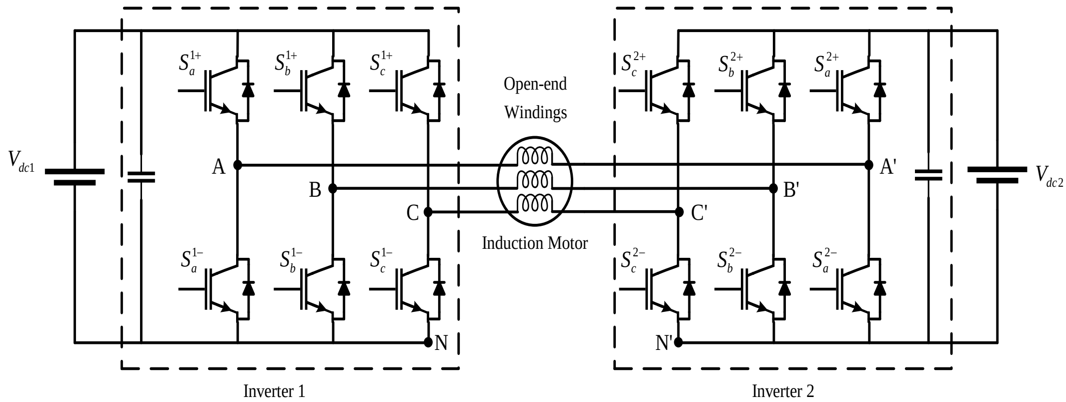

Figure 3. Open-end winding induction machine supplied using dual-inverter

The measures in [23]-[25] can be used to measure the open-end winding drive's phase and leg/pole voltage relationship. The voltage through the open-end windings, for example, can be written as:

$$V_{A^1A^2} = V_{A^1N^1} + V_{N^1N^2} - V_{A^2N^2} \tag{1}$$

$$V_{B^1B^2} = V_{B^1N^1} + V_{N^1N^2} - V_{B^2N^2} \tag{2}$$

$$V_{C^1C^2} = V_{C^1N^1} + V_{N^1N^2} - V_{C^2N^2} \tag{3}$$

where $V_{A^1N^1}$, $V_{B^1N^1}$, $V_{C^1N^1}$, $V_{A^2N^2}$, $V_{B^2N^2}$, $V_{C^2N^2}$ are the voltage of leg/pole, $V_{N^1N^2}$ is the voltage difference in the DC buses' negative rails (also known as common-mode voltages) while $V_{A^1A^2}$, $V_{B^1B^2}$ and $V_{C^1C^2}$ are the voltage of phase. The number of three phase voltage is zero since the DC buses are separated.

As a result, $V_{N^1N^2}$ can be calculated using (1)-(3) is being as:

$$V_{N^1N^2} = \frac{1}{3}[(V_{A^1N^1} - V_{A^2N^2}) + (V_{B^1N^1} - V_{B^2N^2}) + (V_{C^1N^1} - V_{C^2N^2})] \tag{4}$$

By substituting $V_{N^1N^2}$ into (1)-(3), the step voltage can be expressed as:

$$\begin{bmatrix} V_{A^1A^2} \\ V_{B^1B^2} \\ V_{C^1C^2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} V_{A^1N^1} - V_{A^2N^2} \\ V_{B^1N^1} - V_{B^2N^2} \\ V_{C^1N^1} - V_{C^2N^2} \end{bmatrix} \tag{5}$$

For d-q axis component:

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_{A^1A^2} \\ V_{B^1B^2} \\ V_{C^1C^2} \end{bmatrix} \tag{6}$$

The two-level single-sided VSI generates 2^3 switching state combinations. A total of 2^3 x 2^3 or 64 switching state variations are generated when dual two-level inverters are used. In fact, however, only 19 switching state variations are possible. The developed voltage vectors from the 19-switching combination can be divided into four categories: small voltage vectors ($\bar{v}_{sS,1} - \bar{v}_{sS,6}$), medium voltage vectors ($\bar{v}_{sM,1} - \bar{v}_{sM,6}$), largest voltage vectors ($\bar{v}_{sL,1} - \bar{v}_{sL,6}$), and zero or non-active voltage vectors ($\bar{v}_{sZ,0}$), as shown in Figure 4. As shown in Figure 2, the voltage vectors ($\bar{v}_{sL,2}$), which correspond to [S_1, S_2, S_3, S_4, S_5, S_6], can be generated by switching inverter 1 to position V2 and inverter 2 to position V5. In addition, the information of torque and flux status either to increased or decreased and the stator flux position is needed for choosing the suitable switching states from the given look-up table in [26].

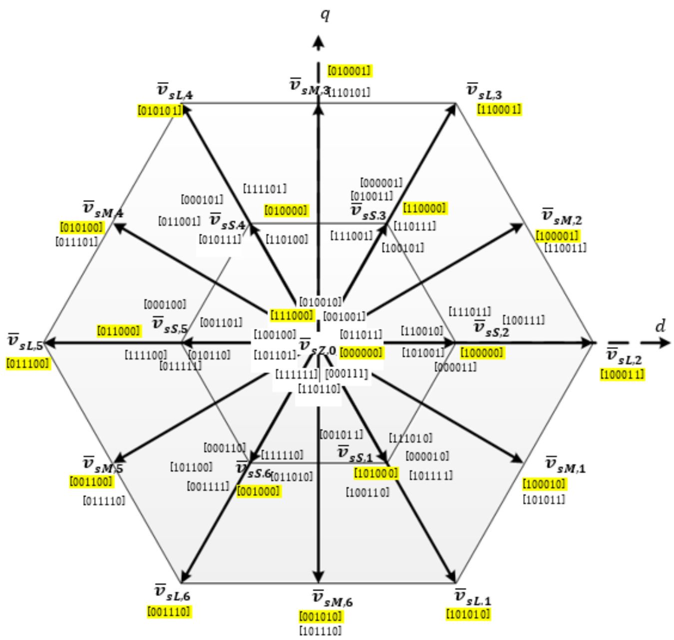

Figure 4. Mapping voltage vector for open-end winding

3. SIMULATION RESULTS

Figure 5 shows the block diagram for the proposed method by using open-end winding. As can see, there is a dual VSI in this method and the look-up is difference when using the single VSI. The look up table will covers all possible voltage vectors including small, medium, and large vectors. Circuit simulation and contrast experiments between the proposed method and the traditional method 2-level DTC have been carried out using MATLAB/Simulink to verify the proposed method. Table 1 lists the unit and control parameters that were used in the experiments.

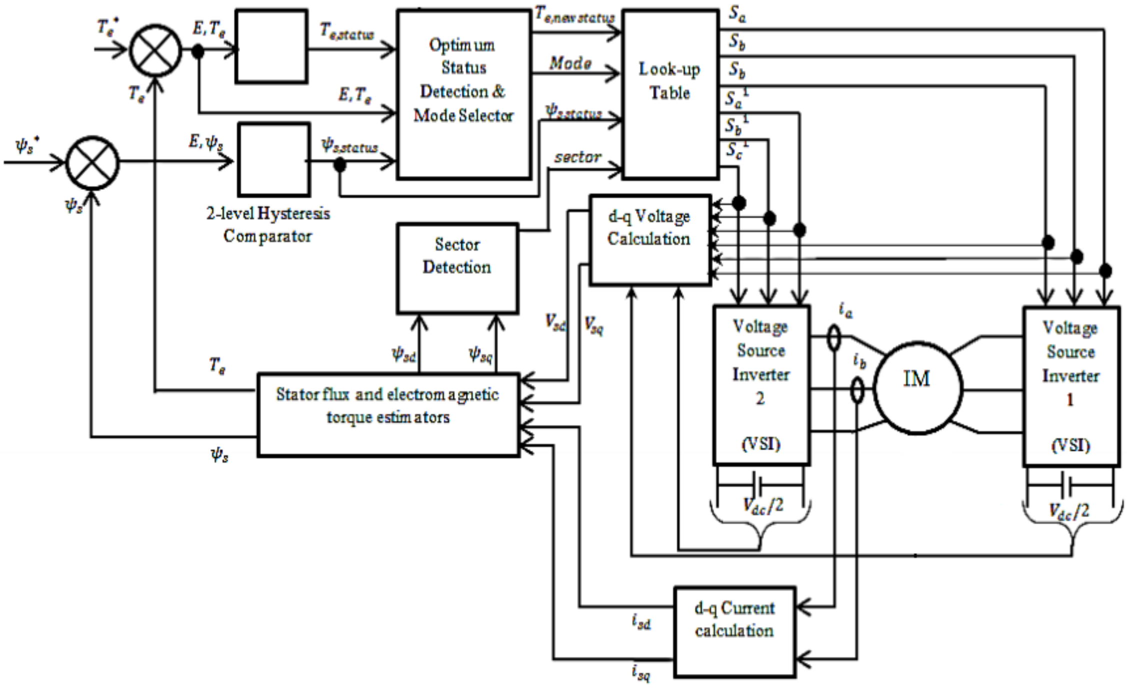

Figure 5. Block diagram of open-end winding induction motor drive

Table 1. Machine and control parameters

Stator resistance, Rs	6.1
Rotor resistance, Rr	6.2298
Stator self-inductance, Ls	0.47979
Rotor self-inductance, Lr	0.47979
Mutual inductance, Lm	0.4634
Number of pole pairs, P	1
Moment of inertia J	0.01
Viscous friction, B	0
DC Voltage, Vdc	240
Sampling Period, DT	5e-6

Figure 6 and 7 shows the results consists of torque, flux, phase current and voltage for single supply and open-end winding of DTC. As shown the different between the waveform is happen after the step change apple from 1Nm to 4Nm. Figure 8 shows the results of torque capability between single supply or open-ended winding. From the results, the open-ended winding maintains regulate towards its reference 4Nm since double DC supply given. Figure 9 shows the comparison of dynamic response for single-side supply and open-end winding. It can be observed that the proposed method by using open-end winding shows the improvement of dynamic response of torque in the induction motor. The performance has slightly increase and provide a better performance due to more possible voltage vectors to be selected to drive the induction motor. The most optimal voltage vector can be chosen with the open-end winding. The torque is changes from 1 Nm to 4 Nm to see the response when sudden torque demand in the applications. The time response for open-end winding, $T_{(OEW)}$=1.11345 which faster compare to time response for single-sided supply, $T_{(SSS)}$=1.11355.

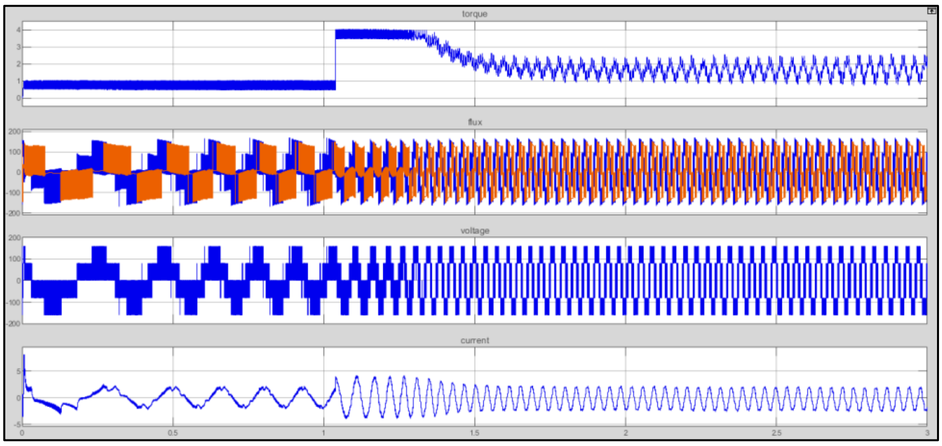

Figure 6. Output Result for Single-Sided Supply of DTC

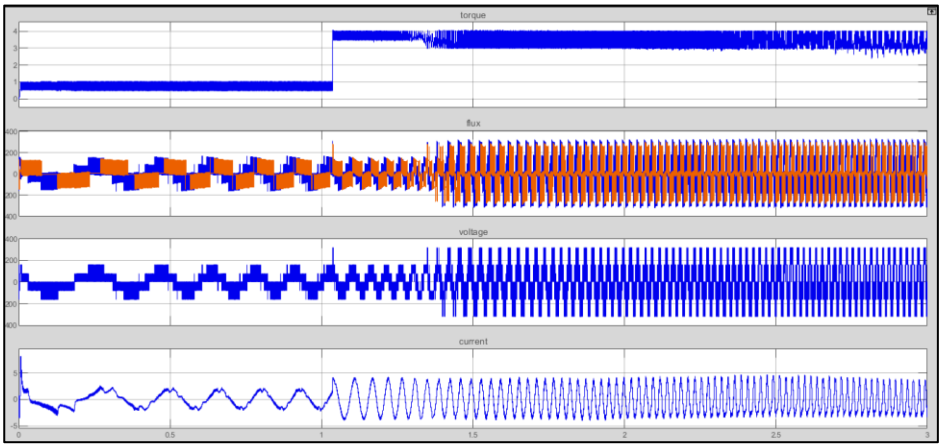

Figure 7. Output Results for Open-End Winding

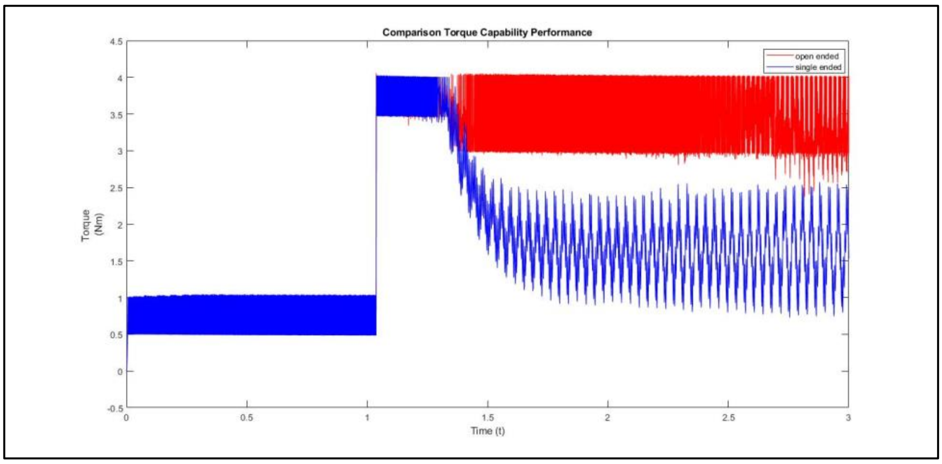

Figure 8. Torque Capability for Single and Open-Ended Winding of DTC

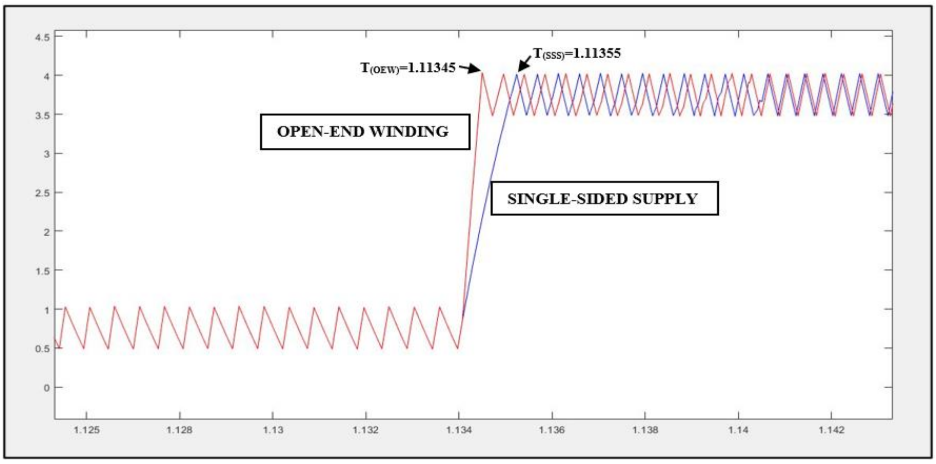

Figure 9. Comparison of dynamic response for single and open-end winding

4. CONCLUSION

This paper shows that by using the open-end winding on induction machine can provide more voltage vector and produced more switching states. With many optional of switching states, the most optimal switching states can be chosen to improve the dynamic response for induction machine. Therefore, using the simulation results, the performance of proposed system by using open-end winding is verified compare to the single sided supply. In simulation results indicates that the response of the open-ended is 1.11345 seconds faster response that the single sided supply. This proposed system by using open-ended winding provides good solution of a dynamic response for induction motor.

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