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A Novel Modified AC/AC Z-Source Converter for Starting Current Reduction for Three-phase Induction Motor

Abstract. *Induction motors inherently have very high current in order to provide sufficient power and torque for the loads when started. This very high current can cause the damage for the motors and other components. Therefore, an additional electronic soft starter such an AC/AC converter is commonly used to reduce this current but the reduced current is still high and relatively has high harmonics. This paper proposes a novel electronic soft starter, a modified AC/AC Z-Source converter for the three-phase induction motor. The proposed soft starter could directly convert AC voltage from a three-phase power supply with constant voltage and frequency by adjusting voltage together with the additional impedance source. The performance in terms of starting current reduction capacity and harmonic reduction capacity of the proposed starter with/without the overlap switching state implementation was examined and evaluated in comparison to the conventional starter with an AC/AC converter. These starter circuits were simulated via the computer program by operating at 3 load torque conditions: without load, half load and full load. The test results showed that the proposed starter with overlap switching state implementation provided the lowest starting current and lowest current harmonic distortion at the full load, following by the proposed starter without the overlap switching state implementation and a conventional starter, respectively. In turn, the proposed starter without the overlap switching state implementation provided the fastest settling times.*

Streszczenie. *Silniki indukcyjne z natury miały bardzo wysoki prąd rozruchowy, aby zapewnić wystarczającą moc i moment obrotowy dla obciążeń, co może spowodować uszkodzenie silników i innych komponentów. Dlatego do zmniejszenia tego prądu stosuje się softstarter elektroniczny, taki jak konwerter AC/AC, ale prąd zredukowany jest nadal wysoki i ma stosunkowo wysokie harmoniczne. W artykule zaproponowano nowatorski elektroniczny softstart, zmodyfikowany konwerter AC/AC Z-Source, do trójfazowego silnika indukcyjnego. Proponowany softstarter mógłby bezpośrednio przekształcać napięcie prądu przemiennego z trójfazowego źródła zasilania o stałym napięciu i częstotliwości poprzez regulację napięcia wraz z dodatkowym źródłem impedancji. Zbadano i oceniono wydajność w zakresie zdolności redukcji prądu rozruchowego i zdolności redukcji harmonicznych proponowanego rozrusznika z/bez implementacji stanu przełączania nakładkowego w porównaniu z konwencjonalnym rozrusznikiem z przekształtnikiem AC/AC. Te obwody rozruchowe symulowano za pomocą programu komputerowego, pracując w 3 warunkach obciążenia momentem obrotowym: bez obciążenia, połowicznego obciążenia i pełnego obciążenia. Wyniki testów pokazały, że proponowany rozrusznik z implementacją stanu przełączania nakładkowego zapewniał najniższy prąd rozruchowy i najniższe zniekształcenia harmoniczne prądu przy pełnym obciążeniu, zastępując odpowiednio rozrusznik bez implementacji stanu przełączania nakładkowego i rozrusznik konwencjonalny. Z kolei proponowany starter bez implementacji stanu przełączania nakładania zapewniał najszybsze czasy rozliczania. (**Nowatorski zmodyfikowany konwerter AC/AC Z-Source do redukcji prądu rozruchowego trójfazowego silnika indukcyjnego**)*

Keywords: starting current reduction, AC/AC converter, soft starter circuits, z-source converter, three-phase induction motor
Słowa kluczowe: redukcja prądu rozruchowego, obwody softstartu, Przetwornica z-source, trójfazowy silnik indukcyjny

Introduction

Electric motors are the machines that convert electrical energy into mechanical energy for useful purposes, which could be found in both dc and ac machines. However, the induction ac electric motors could be the most commonly used motors for many applications due to their advantages of being more affordable, durability, and lower maintenance than the dc electric motors, and its application must be taken into account to drive various loads [1]-[11]. In order to have enough power and torque for use but due to the nature of motors having high starting currents, such high starting currents can damage or reduce the life of the contactor and related equipment. And may result in problems with other systems. This causes the main system to be damaged and unusable [12]-[17]. Therefore, reducing the motor starting current is very important to reduce the potential damage and prolong the service life of the equipment. Which starts the three-phase induction motor with soft start technique it is a method to reduce the current at the start of the engine. Flexible to use there are also less electronic devices to use than variable current reducing motor speed regulators (VFDs).

Therefore, we have an idea to apply a starting current reduction technique with the soft starter circuit controlled by a pulse width modulation (PWM) technique in conjunction with a z source current fed to control the supply of current to a three-phase induction motor. In this concept was conducted via the simulation program, the simulated results of the soft starter circuit compared with the soft starter circuit with z-sources and the soft starter circuit with a current-fed z-source circuit. Consider the behavior of the starting current. In addition, the soft starter circuit with a current-fed z-source provided less harmonics of the current at the maximum load rating.

Experiments

A. A Conventional Soft Starter Circuit

The soft starter circuit is a conventional ac power conversion circuit that connects the load to a induction motor. It consists of 6IGBTs; where all of them (S_1,S_3,S_5) and (S_2,S_4,S_6) were controlled by the technique of adjusting the width of the pulse signal. The circuit and the characteristics of the parameters used in the simulation circuits for the three phase induction motor are shown in Fig. 1. [18]-[20]

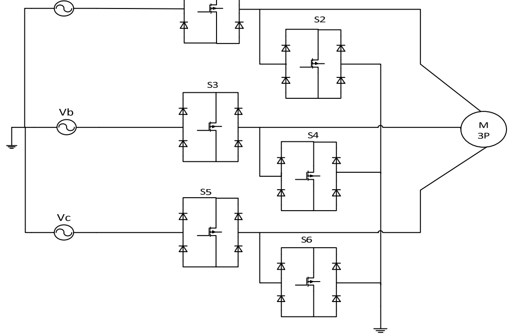


Fig. 1. A conventional soft starter circuit for three phase induction motor [9]

B. A proposed Soft Starter Circuit with Z-Source Circuit

The proposed soft starter circuit is by connecting the X-shapeLC-impedance circuit (or Z-source circuit) between the ac power source and the conventional soft starting circuit as shown in Fig.2.. The impedance circuit consists of the inductors (L_1,L_2,L_3) and the capacitors (C_1,C_2,C_3,C_4,C_5,C_6). The control stratagy is by applied the technique to adjust the width of the pulse signalwhich are described in [21]-[23].

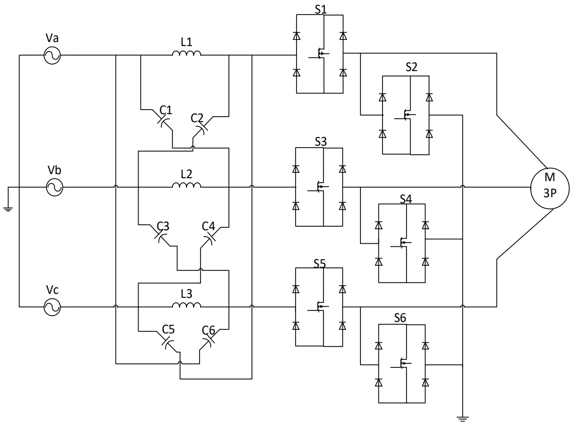


Fig. 2. The proposed soft starter circuit with a z-source circuit

C. The proposed Soft Starter Circuit with a Current-Fed Z-Source

Fig.3(a) presents the proposed circuit topology of this type of the soft starter. The circuit is the same as the soft starter circuit with a z-source inverter presented in Fig.2, but the PWM control strategy is fully the current fed z-source control, which is by implementing the overlap switching states for the circuit [24]-[29], as shown by the switching control signals in Fig.3(b) while the switching codes and their operation states are listed in Table 2.

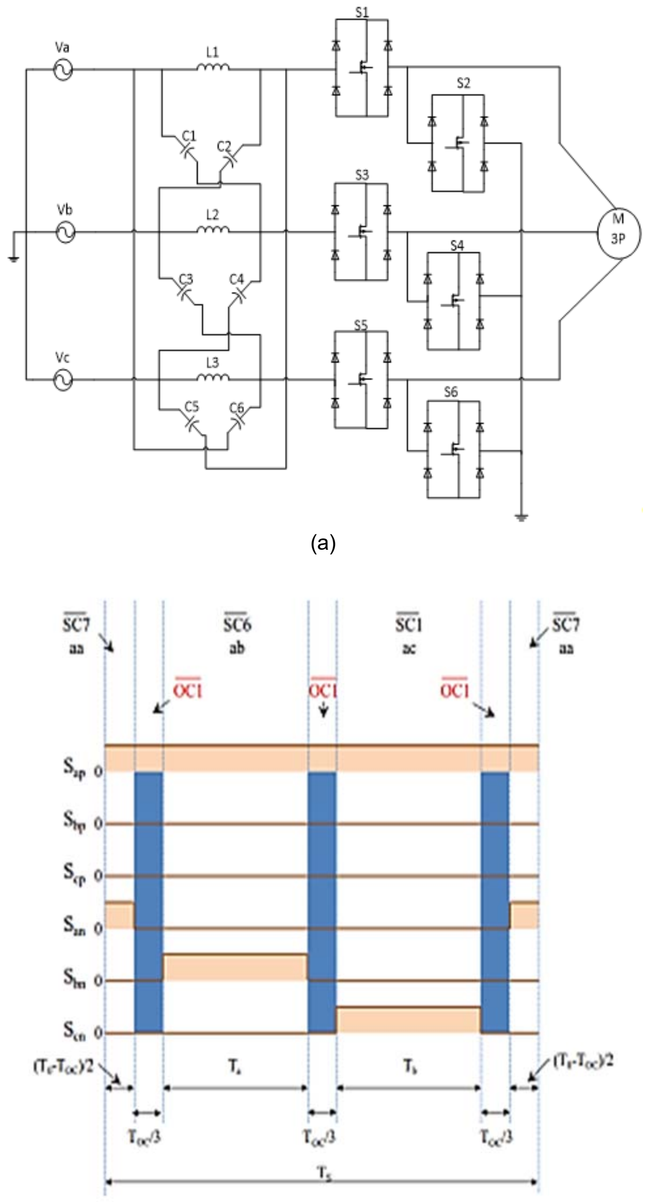
D. Simulation Models of the Motor Drive Systems

Fig. 4. (a)-(c) showed the MATLAB-Simulink simulation models for the conventional soft starter circuit, the proposed soft starter circuit with a z-source circuit and the proposed soft starter circuit with a current-fed z-source circuit. These starter circuit were tested at 3 cases of load torque: Case 1: without load at 0 Nm. Case 2: half full load torque at 13 Nm. and Case 3: full load torque at 26 Nm.

The three-phase induction motor of the MATLAB program in Simulink's blog was used to simulate the circuit to reduce the starting current. It was a three-phase induction motor with power of 5.4 hp, voltage 400 V, frequency 50 Hz with parameters as listed in Table 1.

Table 1. Parameters of a 5.4 HP three-phase induction motor

Parameter	Value	Description
R_s	1.405	Stator resistance
R_r	1.395	Rotor resistance
L_{ls}	0.005839	Stator inductance
L_{lr}	0.005839	Rotor inductance
L_m	0.1722	Mutual inductance
J	0.0131	Inertia
P	2	Motor pole



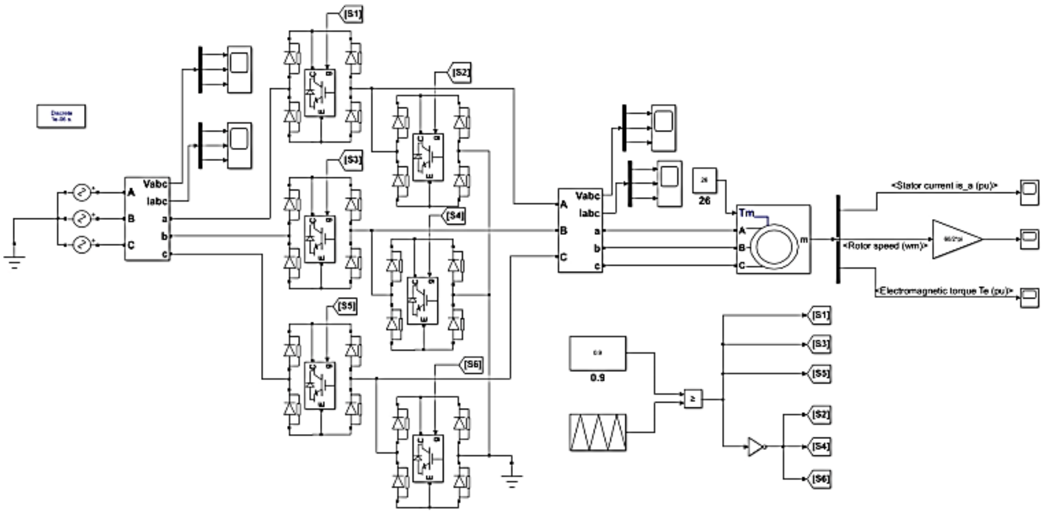
(a)

(b)

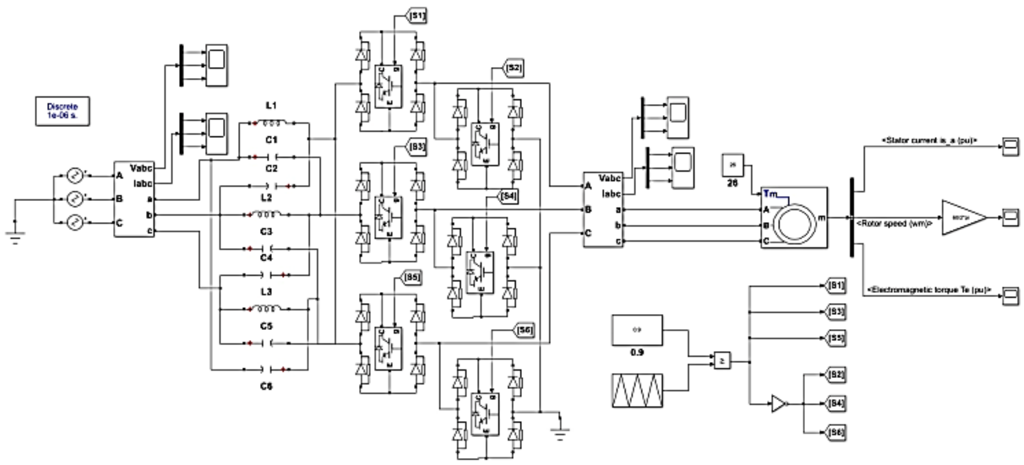
Fig. 3. The proposed soft starter circuit with a current-fed z-source [14]: (a) circuit structure and (b) switching signals for each particular switching device per one cycle

Table 2. Switching state control strategy for the proposed soft start circuit with a current-fed z-source according to Fig.3 [14]

Open-circuit Switching State	Switching State						Open-Circuiting DC-link rail (s)
	S_{ap}	S_{bp}	S_{cp}	S_{an}	S_{bn}	S_{cn}	
OC1	1	0	0	0	0	0	Lower
OC2	0	1	0	0	0	0	Lower
OC3	0	0	1	0	0	0	Lower
OC4	0	0	0	1	0	0	Upper
OC5	0	0	0	0	1	0	Upper
OC6	0	0	0	0	0	1	Upper
OC7	0	0	0	0	0	0	Lower and Upper



(a)



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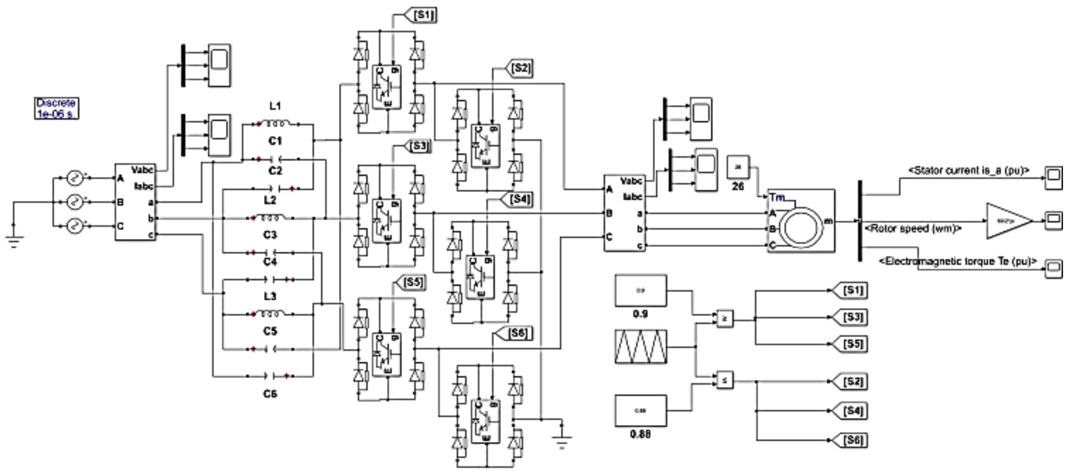


(c)

Fig. 4. The MATLAB-Simulink simulation models for the motor drive systems : (a) the soft starter circuit; (b) the soft starter circuit with z-sources; and (c) the soft starter circuit with a current-fed z-source

Results

Fig. 5-7 show the simulated results obtained from the circuit shown in Fig. 4(a)-(c), respectively. There were 3 test scenarios, which provided: comparison of the starting current for both soft starter circuit, the soft starter circuit with z-sources and the soft starter circuit with a current-fed z-source when applied at 3 cases of load torque:

Case 1: without load at 0 Nm

Case 2: half full load torque at 13 Nm

Case 3: full load torque at 26 Nm

The testing conditions of a soft starter circuit with a load of a three-phase induction motor, tested at m=0.9, switching frequency of 10 kHz with a constant input voltage of 400 V. The soft starter circuit with z-sources at m = 0.9, switching frequency of 10 kHz with a constant input voltage of 400 V. The capacitor circuit impedance ($C_1=C_2=C_3=C_4=C_5=C_6$) was equal to 500 μF the circuit impedance inductance ($L_1=L_2=L_3$) was equal to 1 mH. The soft starter circuit with a current-fed z-source test at m_1 = 0.9 and m_2 = 0.88 switching frequency of 10 kHz with a constant input voltage of 400 V. The capacitor circuit impedance ($C_1=C_2=C_3=C_4=C_5=C_6$) was equal to 500 μF the circuit impedance inductance ($L_1=L_2=L_3$) was equal to 1 mH. The results of the test are as follows:

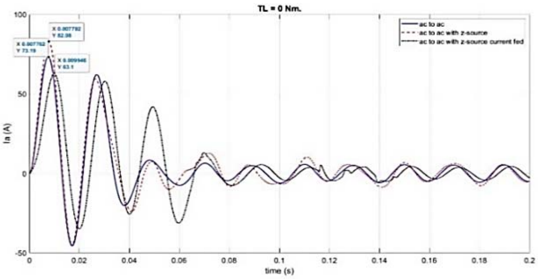


Fig. 5. Starting current for the Case 1: at without load

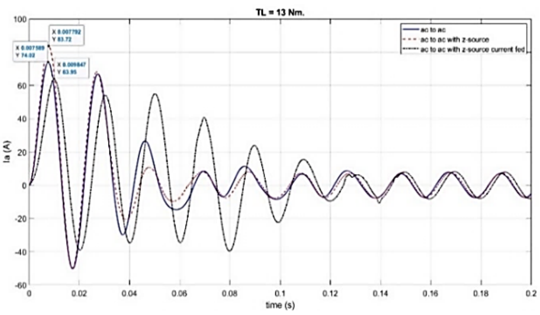


Fig. 6. Starting current for Case 2: at half full load torque (13 Nm)

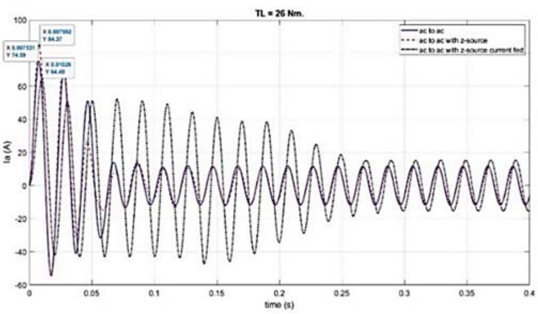


Fig. 7. Starting current for Case 3: at full load torque (26 Nm)

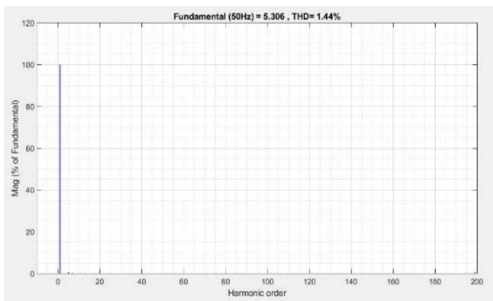
From the simulation results of a three-phase induction motor drive circuit With the soft starter circuit, the soft starter circuit with z-sources and the soft starter circuit with a current-fed z-source at all 3 load driving conditions, the results of the maximum peak starting current can be summarized in Table 3.

Table 3. Maximum peak starting current

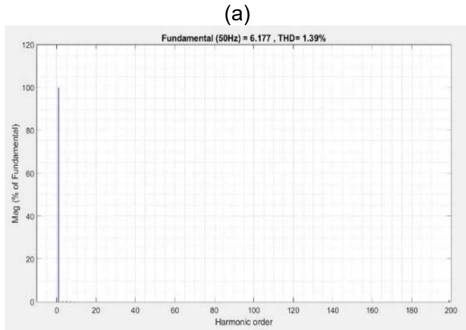
Case: Test Condition	Maximum Peak Starting Current (A)		
	The Conventional soft starter circuit	The proposed soft starter circuit with z-sources	The proposed soft starter circuit with a current-fed z-source
Case 1: Without load	73.19	82.98	63.1
Case 2: Half full load torque	74.02	83.72	63.95
Case 3: Full load torque	74.59	84.37	64.49

From Table 3, it can be concluded that the starting current peak of the soft starter circuit with a current-fed z-source compared to the soft starter circuit and the soft starter circuit with z-sources. It was the lowest value across the load torque test range. There was a 13.78% reduction in starting current in Case 1 compared to the soft starter circuit and 23.95% compared to the soft starter circuit with z-sources. The starting current of Case 2 was reduced by 13.6% compared to the soft starter circuit and 23.61% compared to the soft starter circuit with z-sources. The starting current of Case 3 was reduced by 13.54% compared to the soft starter circuit and 23.56 in the soft starter circuit with z-sources. When applying the simulation results with the program MATLAB-Simulink all 3 circuits are compared, which determines the device used parameters. It is found that when the impedance supply circuit was added to the soft start circuit controlled by PWM technique and short-circuit condition adjustment. This allows to reduce the starting current for all torque changes at the load.

From the simulation of the operation of 3 circuits at the load driving conditions in all 3 cases, considering the amount of harmonics of the output current. The results of the test are as follows:



(a)



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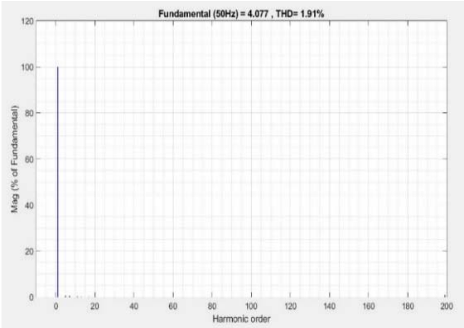

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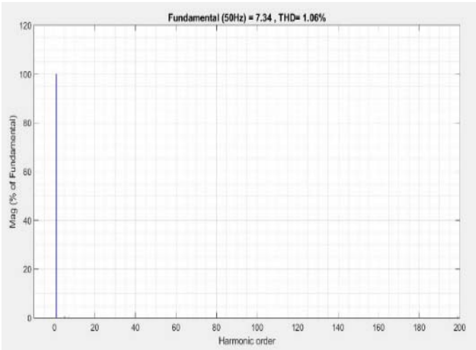
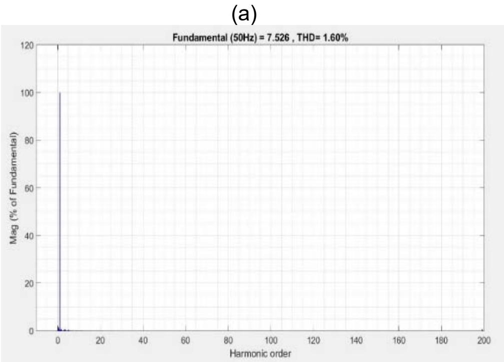
Fig. 8. Harmonics of the output current of Case 1 without load: (a) the soft starter circuit; (b) the proposed soft starter circuit with z-sources and (c) the proposed soft starter circuit with a current-fed z-source



(a)



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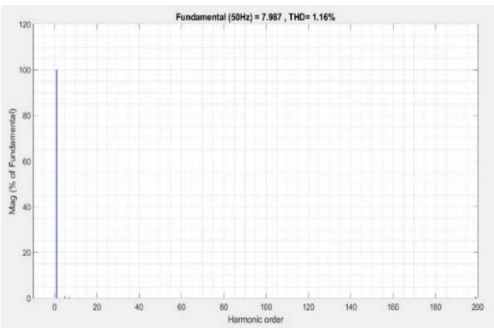
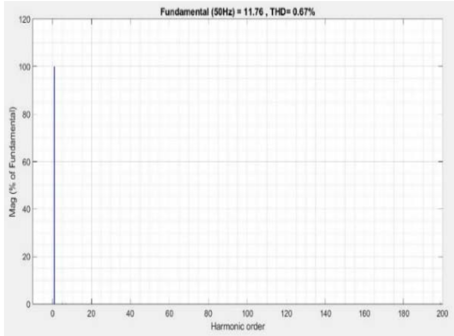
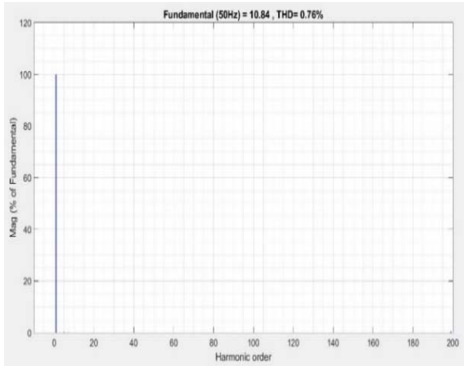


(c)

Fig. 9. Harmonics of the output current of Case 2 half full load: (a) the soft starter circuit; (b) the proposed soft starter circuit with z-sources and (c) the proposed soft starter circuit with a current-fed z-source



(a)



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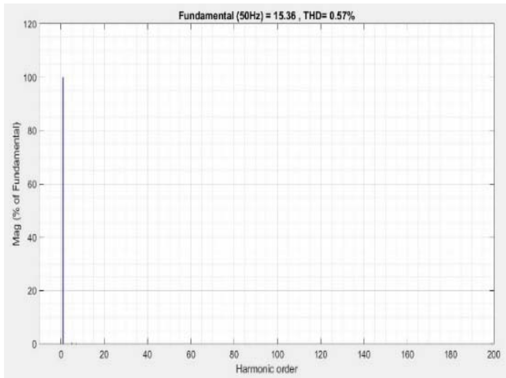

(c)

Fig. 10. Harmonics of the output current of case 3 full load: (a) the soft starter circuit; (b) the proposed soft starter circuit with z-sources and (c) the proposed soft starter circuit with a current-fed z-source

From the simulation results of a three-phase induction motor drive circuit for all 3 load conditions, the harmonics of the current can be summarized as shown in Table 4.

Table 4. Total Harmonics Distortion of output current (%)

Test Condition	Maximum Peak Starting Current (A)		
	The Conventional soft starter circuit	The proposed soft starter circuit with z-sources	The Conventional soft starter circuit
Case 1: Without load	1.44	1.39	1.91
Case 2: Half full load torque	1.06	1.60	1.16
Case 3: Full load torque	0.67	0.76	0.57

From Table 4, it can be seen that the proposed soft starter circuit with a current-fed z-source achieved the lowest harmonic distortion contents when compared with the soft starter circuit, the harmonic amount of current was reduced by 14.93%, and compared to the soft starter circuit with z-sources, it had a hard amount. The harmonic of the current was reduced by 25%.

Conclusions

This paper proposed the soft starter circuit with a z-source converter and the soft starter with a current-fed z-source converter. From the simulation study of these circuits with an attempt to reduce the starting current of a three-phase induction motor. It was found that the soft starter circuit with a current-fed z-source achieve the lowest starting current for all the torque tests at the load in all 3 test condition: without load, half load (13 Nm) and full load (26Nm) for maximum peak current of 63.1 A, 63.87 A 64.49 A, respectively; while other in the range of 73-85A. In addition, the proposed soft starter circuit with a current-fed z-source provided the harmonics of the current at the maximum load rating with the lowest value as THD_i = 0.57% compared to 0.67-0.78 of other topologies.

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