INVESTIGATION OF INTELLIGENT CONTROLLERS FOR VARIABLE SPEED PFC BUCK-BOOST RECTIFIER FED BLDC MOTOR DRIVE

P. SIVAKUMAR
RVS Educational Trust Group of, Institution
Electrical and Electronic Engineering,
Dindigul, Tamilnadu, India.
impsiva@gmail.com

V. RAJASEKARAN,
PSNA College of Engineering, Technology,
Electrical and Electronic Engineering,
Dindigul, Tamilnadu, India.
hodeee@psnacet.edu.in

K. RAMASH KUMAR,
Karpagam College of Engineering,
Electrical and Electronic Engineering
Coimbatore, Tamilnadu, India.
ramash1210@yahoo.co.in

Abstract: *This article studies on a design and implementation of intelligent controllers (ICs) for variable speed power factor corrected (PFC) buck-boost rectifier (BLBBR) fed BLDC motor drive without sensing its motor speed. A PFC BLBBR worked in discontinuous conduction mode (DCM) to offer a good PFC at A.C mains. The main advantages of the designed model have purging of front-side diode bridge rectifier that can lead to minimize the ON/OFF losses connected with it, speed control is done without sensing speed feed-back and good PFC. The classical linear proportional integral (PI) controller is not able to manipulate the output voltage and produces poor dynamic characteristics during the large line and large disturbances. In order to improve the good output voltage/speed regulations and dynamic characteristics of a PFC BLBBR fed BLDC motor drive, a ICs is designed. The ICs are fuzzy logic controller (FLC) and neuro controller (NC). The FLC rules are framed with help of the converter behaviour without analytical modelling. The NC data's are arrived from the conventional controller and then these data's are trained using feed-forward back propagation algorithm. The performance of the PFC BLBBR fed same motor drive with designed NC is validated at different operating conditions by making of MATLAB/Simulink models in comparison with fuzzy logic controller (FLC) and PI controller. The simulation results are presented to show the efficacy of the developed system.*

Keyword: *AC-DC power conversion, PFC, buck-boost converter, neuro controller, BLDC motor drive, linear PI controller and FLC.*

1. Introduction.

In current days, the enhancement of power quality (PQ) at A.C mains is very important and also, it follows as per the international PQ standards like IEC 61000-3-2. Generally, the power factor corrected (PFC) converter fed D.C motor drive applications maintains the power factor greater than 0.9 and total harmonic distortion (THD) smaller than 5% for class-D (in 600W, less than 16A, single phase) [1]. The diode bridge rectifier (DBR) based PFC fed D.C motor drive does not flow the sinusoidal current at AC mains because of the AC voltage is lower than the DC link capacitor voltage, as the power diodes are reverse polarized in that time period; yet, it flows a more current while the AC voltage is higher than the DC link capacitor voltage [2]. As a outcome, several PQ problems occur at A.C mains including poor power factor, more THD and high peak factor (PF) of AC mains current etc. These PQ crises become more rigorous for the utility as many such drives are employed all together at different locations. The many of the PFC based AC-DC converter using control methodologies has been well presented and surveyed in [3]-[5]. The zeta converter topology based PFC for trapezoidal flux distribution based motor drive is reported [6]. However, design part and PQ part of this article is not clearly presented. The complete review of control methodologies for various DC-DC converters is surveyed in [7]. From this article, current mode controllers, classical linear controllers, nonlinear sliding mode controller (SMC) and FLC has been well discussed. Also, among these controllers FLC is best controller and produced accurate results. The PFC cuk' fed permanent magnet BLDC motor drive is reported in [8]. Still, this article has presented more number of sensors, current controller and speed controller that can lead to more cost and complexity in implementation. The isolated AC/DC off-line high PFC one power switch LED with FLC is well executed [9]. A one stage one power switch LED based on Class E converter is reported [10]. However, the buck-boost converter is worked with resonant converter to provide the soft switching. A current sensorless PFC control for LED lamp driver is addressed in [11]. However, the designed controller has produced more peak overshoots particularly in line and load variations. Power factor enhancement of AC/DC converter fed separately excited DC motor with R-L-C filter is reported [12]. The PFC buck boost converter fed trapezoidal flux distribution based motor drive using classical linear proportional-integral (PI) controller has been presented.

The classical linear PI controller and proportional dual integral controller (PDIC) for DC-DC converters have been well focused in [13]-[15]. Still, the classical linear controllers are very sensitive to converter circuit components modifications, input supply voltage and load resistance variations. An intelligent controllers (ICs) (example: FLC and neural controller (NC)) are kind of non-linear controller in nature and implementation of ICs for traditional buck converter, boost converter, and Luo-Converters has been addressed in [16]-[19]. The main merits of designed ICs have good stability under the large line and load disturbances, needs an accurate mathematical model of the neither system nor intricate calculations and uncomplicated implementation of control design. From the above survey, it is clearly showed that the PFC buck-boost rectifier (BLBBR) fed BLDC motor drive using ICs has not been reported.

Therefore, in this article, it is to design the ICs to regulate the output voltage/speed of PFC BLBBR fed BLDC motor drive operated in discontinues conduction mode (DCM) without sensing the BLDC motor speed. In this article, two ICs are selected to design (FLC and NC) for this PFC BLBBR. The ICs for designed model is implemented using in matrix laboratory (MATLAB)/simulation link (Simulink).

The organization of this article is as follows. The circuit operation of the PFC BLBBR fed BLDC motor is discussed in part 2. Part 3 presents the complete controllers design for this converter model. The results of the converter using ICs and classical PI controller in the various working states are dealt in sections 4. The conclusions are addressed in section 5.

2. Operation and design of circuit parameters of PFC bridgeless buck-boost rectifier fed loads.

A. Description of topology

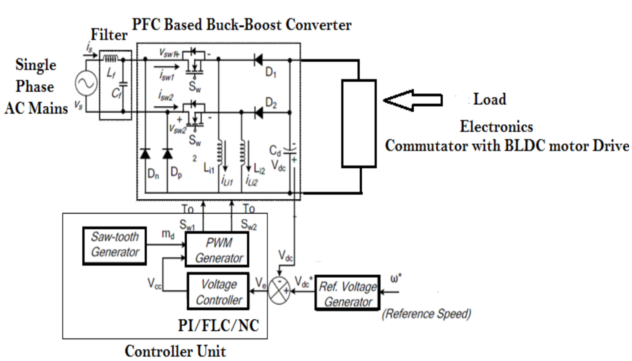


Fig.1. PFC BLBBR fed BLDC motor drive.

The topology of PFC BLBBR fed BLDC motor drive loads is illustrated in Fig.1. The parameters of BLBBR are designed such that it works in DCM to found an intrinsic PFC at A.C supply mains and also, voltage/speed control of dissimilar loads is attained. The performance analysis of designed model is corroborated for extensive choice of speed control with proficient PQ at AC supply mains. PFC BLBBR have the minimum quantity of elements as well as less quantity of ON devices in each half cycle of supply voltage.

B. Modes of Operation for PFC BLBBR

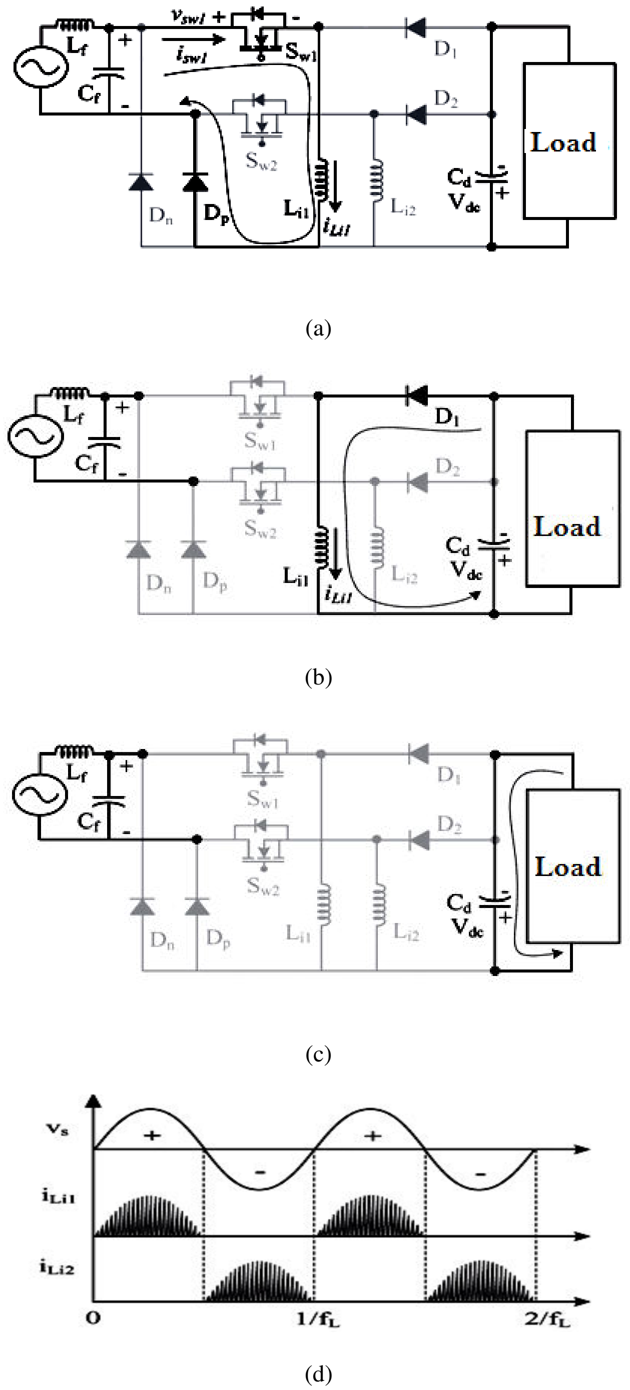
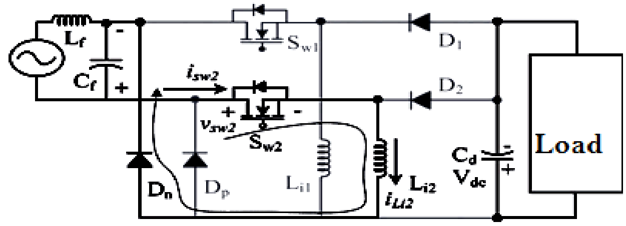
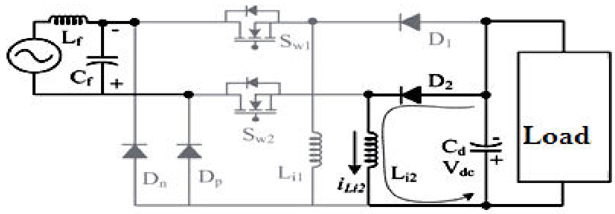


Fig.2. Modes of working of PFC BLBBR fed BLDC motor drive during switching period in positive half cycle, (a) State I, (b) State II, (c) State III and (d) Supply voltage during both half cycle.

The working of the designed converter can be divided into two part that comprise the working during the +ve and –ve half-cycles of main supply voltage and in the whole T. PFC BLBBR can be functioned with help of the S_{w1} and S_{w2} in both the +ve and the -ve half cycles correspondingly.



(a)



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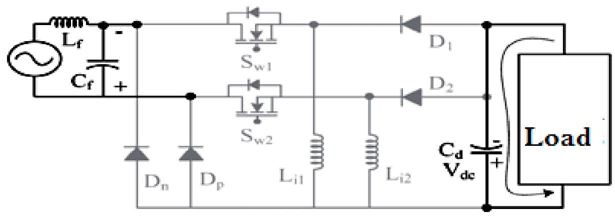
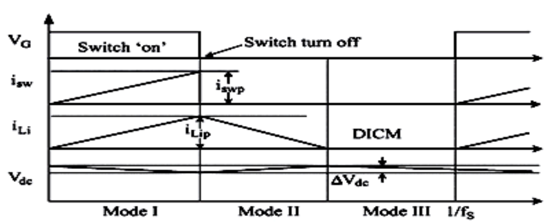


(c)



(d)

Fig.3. Modes of working of PFC BLBBR fed BLDC motor drive during switching period in negative half cycle, (a) State I, (b) State II, (c) State III and (d) Waveforms in complete switching cycle.

During the +ve half cycle of the input, the flow of electron starts from the supply to S_{w1}, inductor L_1 and the DC-link capacitor C_d gets charged via. the diodes D_1 and D_p as depicting in Fig. 2 (a) to Fig. 2(c). Likewise in negative half cycle the switch S_{w2}, L_2, and D_2 and D_n conduct as illustrated in Fig. 2 (a) to Fig. 2 (c). During the DCM working of this BLBBR, the i_{L1} becomes non-continuous for certain in a T. Fig. 2(d) indicate the theoretical waveforms of various parameters in positive and negative half cycle of source voltage.

States of working under whole switching:

There are three states of workings possible for each positive/negative half cycle of source voltage. The modes of working for positive half cycle as follows;

State I: S_{w1} is ON, Inductor gets charged.

In this state the switch S_{w1} starts conducting and the inductor L_1 gets charged and the loop gets closed through the diode D_p. The inductor current keeps on increasing in this mode. On the other hand, the capacitor C_d supplies the load (DC Motor) as depits in fig. 2 (a).

State II: $S_{w1}$is OFF, Inductor gets discharged.

In state II working (see Fig. 2 (b)), switch S_{w1} is in open state and the energy stored in inductor L_{i1} is transferred to DC link capacitor C_d till the inductor is entirely de-energized. The L_{i1} falls and touches to zero as shown in fig.3 (d).

State III: $S_{w1}$is OFF, Inductor fully discharged.

In this state, L_{i1} enters non-continuous conduction. Therefore, current I_{Li1} becomes null for the respite of T. From the fig. 2(c), none of the switch or diode is conducting in this state and C_d supplies energy to the load. As a result, voltage V_{dc} across C_d starts falling. The working is replicated when switch S_{w1} is closed again after a T.

Likewise, for the -ve half cycle of the source voltage, the switch S_{w2}, Inductor L_{i2}, power diodes D_2 and D_n work for voltage control and PFC (refer Fig. 3 (a) to 3 (c)).

C. Specifications of PFC BLBBR fed BLDC motor drive

Table 2. The designed specification of the PFC BLBBR fed BLDC motor drive

Parameters name	Symbol	Value
Input Voltage	V_S	258V (Peak Value)
Output Voltage	V_o	150V
Inductor	L_{i1} & L_{i2}	35µH
Inductor	L_f	0.6mH
Capacitors	C_d	2200 µF
Nominal switching frequency	f_s	20kHz

BLDC Motor Rating: 4 poles, Prated (rated power)= 251.321W,Vrated (rated dc link voltage) = 200V, T_{rated} (rated torque)=1 .21 N·m, ω_{rated} (rated speed) = 2000 r/min, K_b (back EMF constant) = 79V/kr/min, K_t (torque constant)= 0.744 N·m/A, R_{ph} (phase resistance) = 14 .56 Ω, L_{ph} (phase inductance) = 25 .771 mH, and J (moment of inertia)=1.333×e-4 N·m/A2. Motor gain constant =0.10.

3. Design of controllers

The main aim of this section is discusses about the voltage controller design for PFC BLBBR operated in DCM fed BLDC motor drive. There are three controllers are designed here for regulating output voltage and improved the PFC BLBBR namely PI controller, FLC and NC.

A. Design of classical linear PI controller

A PI controller is picked for offering the outstanding output voltage regulation and minimized steady state error for the PFC BLBBR fed this motor drive. The modeling of this motor drive is used in [8]. In this article, the classical linear PI controller parameters of the same converter (proportional gain (K_p) and integral time (T_i)) are calculated with Zeigler – Nichols tuning method (K_p= 0.16 and K_i=400) [20]-[24].

B. Design of FLC

The benefits of the FLC over classical linear controller are that it does not need any complex mathematical models, which are always essential for highly complex non-linear models. The FLC use the heuristic reasoning ability based on the knowledge of human experience of the model [23-24].

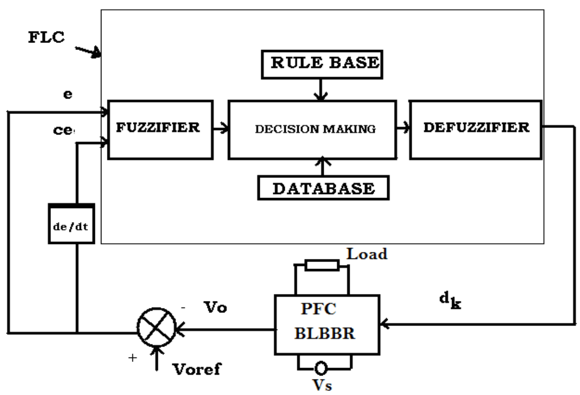


Fig.4. Structure of FLC for PFC BLBBR fed BLDC motor drive.

The structure of the FLC for designed converter is represented in Fig. 4. In this article, the sugeno-method FLC is exploited as an outer voltage loop to manipulate the power switches of the PFC buck-boost converter. The applied inputs and output of the FLC for the converter is depict in Fig. 4 (a) to (c). The voltage error (e) and its change in error (ce) of this PFC buck-boost converter is used as a input the FLC and the output is o (indicate the control signal for the power switches of this converter). For expediency, the math values of the inputs as well as the output of the FLC can be uniformed and uttered in Figs. 4a, 4b and 4c (o = [-0.5 -0.4 -0.3033 0 0.4 0.3033 0.5]) and its equivalent fuzzy sets are [NB, NM, NS, Z, PS, PM, PB] where, NB (negative big), NS (negative small), Z (zero), PS (positive small), PM (positive medium), PB (positive big), respectively. The function of memberships is e, ce, and o specified in Fig. 4a to 4c. The assortment of FLC rules is totally depends on dynamic activities of the PFC buck-boost converter. In this article, 49 rules are framed and listed in the Table 2. Then, the weighted average defuzzification-method is applied to complete the total the FLC process.

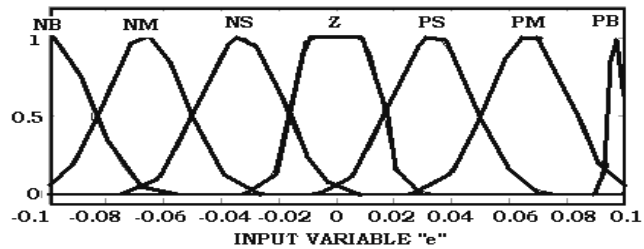


Fig. 4a**.** Graphical diagram of gauss membership functions for "e".

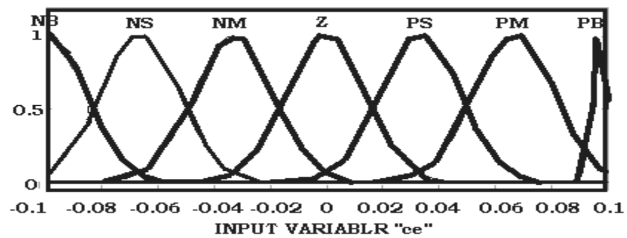


Fig.4b. Graphical diagram of gauss membership functions for "ce".

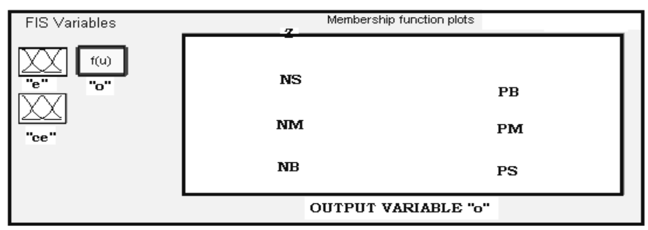


Fig.4c. Graphical diagram of gauss membership functions for "o".

Table. 2 Fuzzy rule base table of PFC BLBBR.

ce \ e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	PM	PM	NB	NS	NM	NB
NS	NB	NB	NB	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	NB
PS	NM	NS	NM	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	NB	PB
PB	Z	PS	PM	PB	NM	PB	PB

C. Design of neuro controller

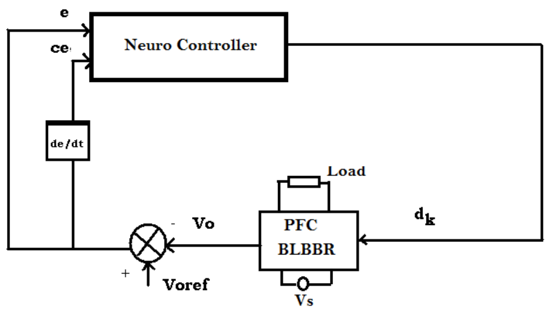
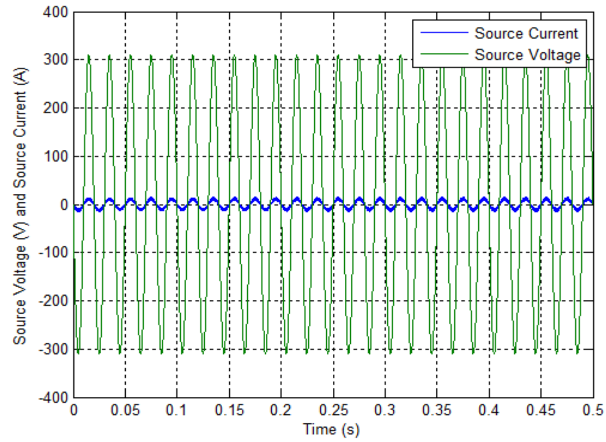


Fig.5. Structure of NC for PFC BLBBR fed BLDC motor drive.

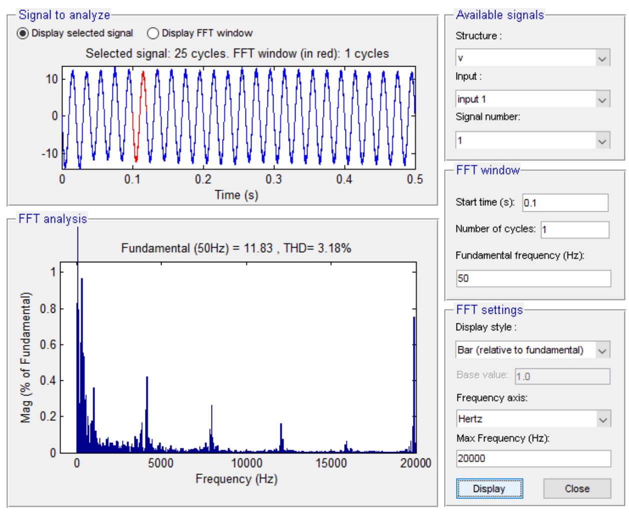
The data of inputs/output are essential for training of NC in off-line of the voltage transfer gain of the PFC BLBBR fed BLDC motor drive. The group of date is made suitably loaded to pledge stable working because no extra learning will occur after training of the NC. A feed-forward back-propagation algorithm (FFBPA) is utilized for preparation of the generated NC network [25]. The PURELIN function, which has a slope fall with momentum weight and bias learning, is applied in this model. The learning arises according to the learning specifications: learning rate=0.01 and momentum constant t = 0.9. The mean square error (MSE) is the main performance criteria applied in this NC that computes the network consistent with the MSE between the goal and calculated output. The smallest amount MSE that can be attained in this NC network is 1e-5. For a FFBPA, the derivative of the activation function (AF) is required. As a result, the AF chosen should be differentiable. The tan sigmoid function (SF) fulfills this necessity and also, it is the generally applied squashy-restricting AF. The SF is reasonably universal to apply linear output nodes to create learning simpler and by a linear activation function (LAF) in the output layer don't 'squash' (compress) the value of output. Then, a bi-polar SF and a LAF are utilized for the hidden and output layers, respectively. The trials have been passed out to determine optimum accuracy with a small quantity of neurons per layer. The developed neural network consists of one neuron (in the input layer), three neurons (in the hidden layer), and one neuron (in output layer). The maximum number of neurons for the hidden layer is selected as three because the number of epochs for training the NC is decreased significantly. In this case, the tansig function is obtained for the hidden layer approximately 20 epochs. The input to the NC (see the Fig.5) is output voltage error (refer fig.5). The output of the NC is the adjusted duty cycles of the PFC BLBBR to regulate the output voltage.

4. Simulation results and discussions

The main function of this part is to discuses about the simulation results of PFC BLBBR fed BLDC motor drive with designed controllers such as PI controller, NC and FLC. The performance of designed model is corroborated at different operating conditions with their specifications are cataloged in Table 1. Fig. 6 show the simulated results of the source current, source voltage, inductor currents and THD of PFC BLBBR fed BLDC motor using designed NC. From these results, it is clearly found that the source current THD of PFC BLBBR has produced 3.18% and source current and voltage maintained in phase using NC.



(a)



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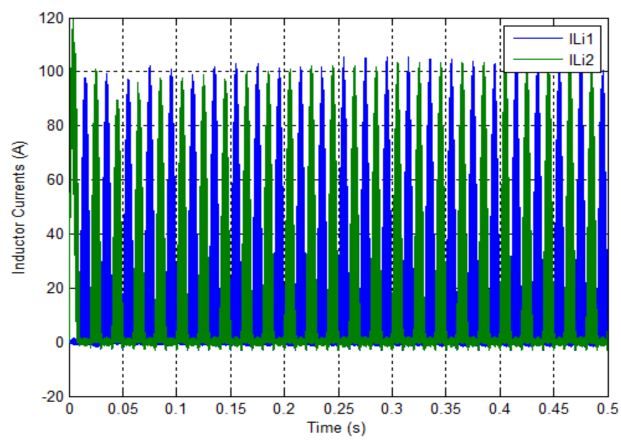


(c)

Fig. 6. Simulated results of PFC BLBBR fed BLDC motor with NC, (a) source current and voltage, (b) total harmonics distortion, and (c) inductor currents.

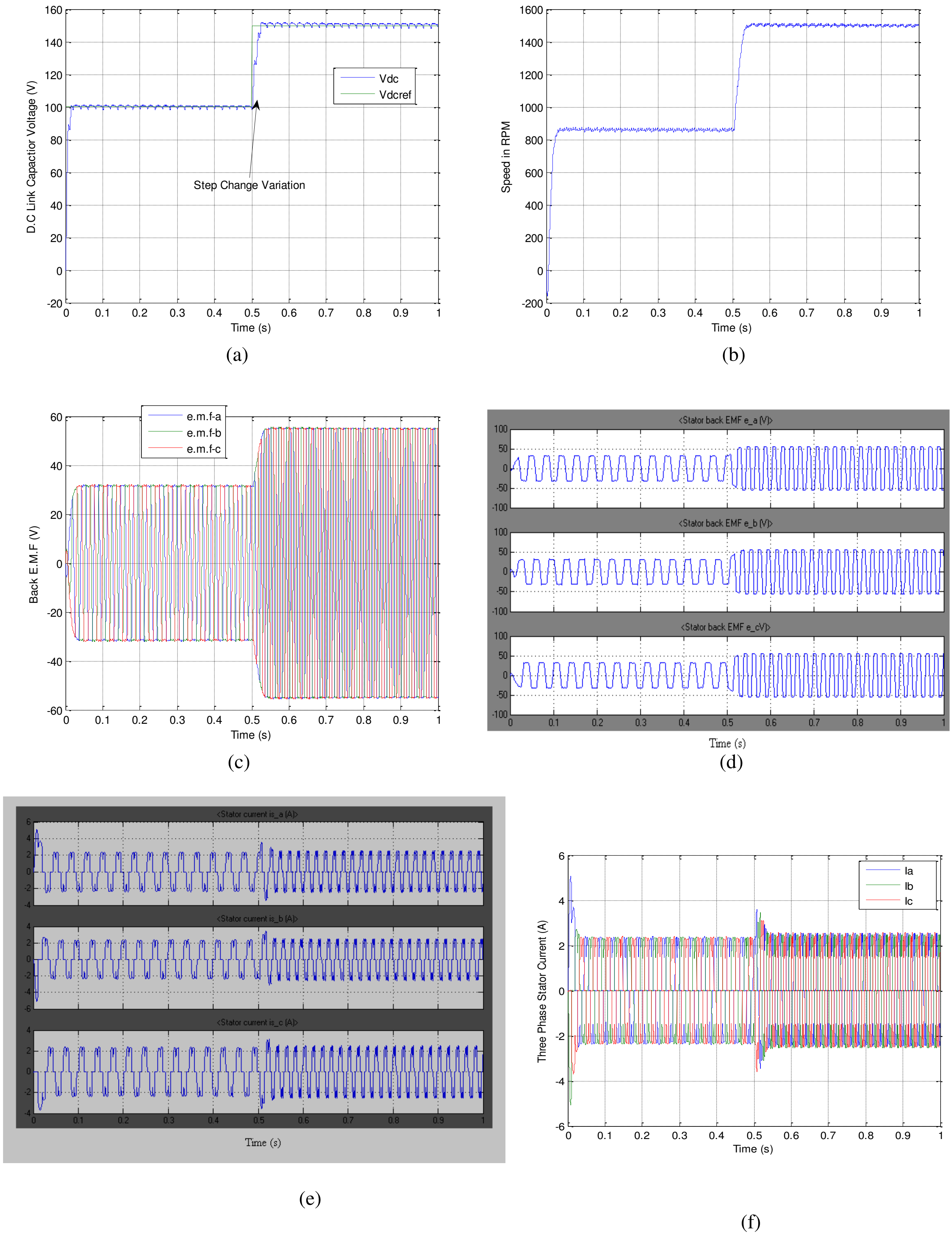
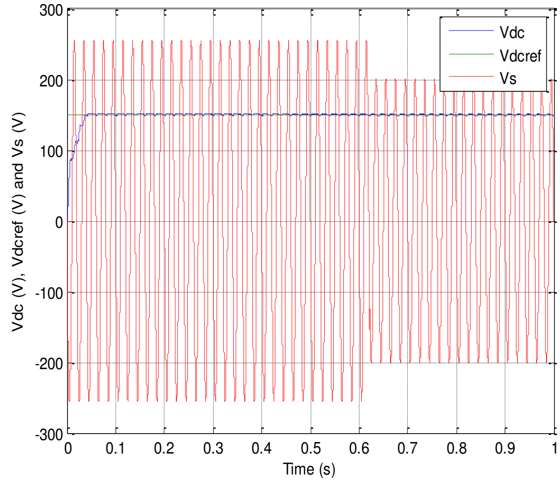
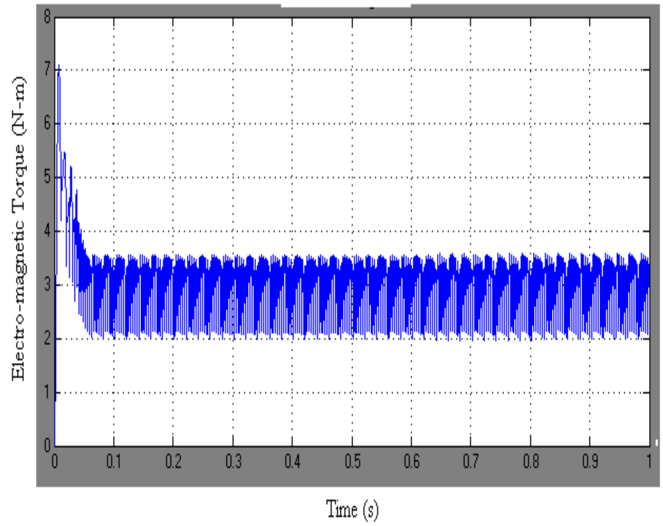


Fig. 7. Simulated responses of PFC BLBBR fed BLDC motor with NC for step change reference DC link voltage from 100V to 150V, (a) measured and reference DC link voltage of the converter, (b) speed, and (c) back emf, (d) zoomed back emf, (e) zoomed stator currents and (d) stator currents.



(a)



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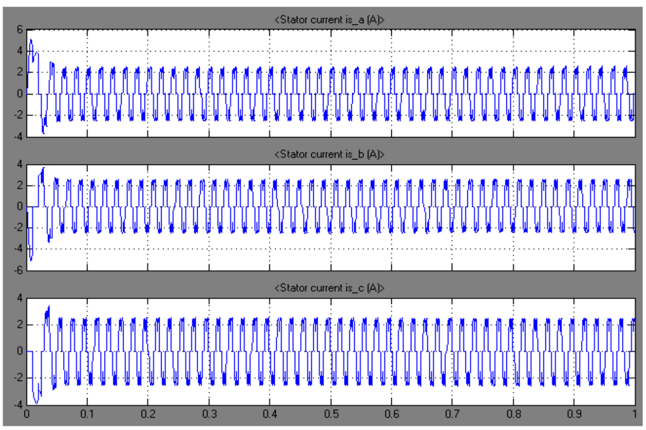

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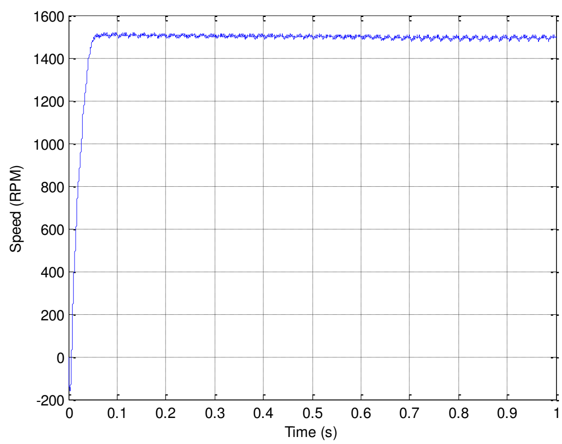

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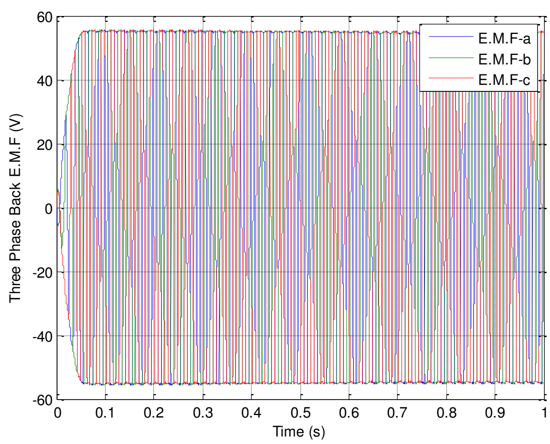

(e)

Fig. 8. Simulated responses of PFC BLBBR fed BLDC motor with NC controller for source voltage change from 258V to 200V, (a) source voltage, measured and reference DC link voltage of the converter, (b) torque, and (c) zoomed stator currents, (d) speed and (e) back emf.

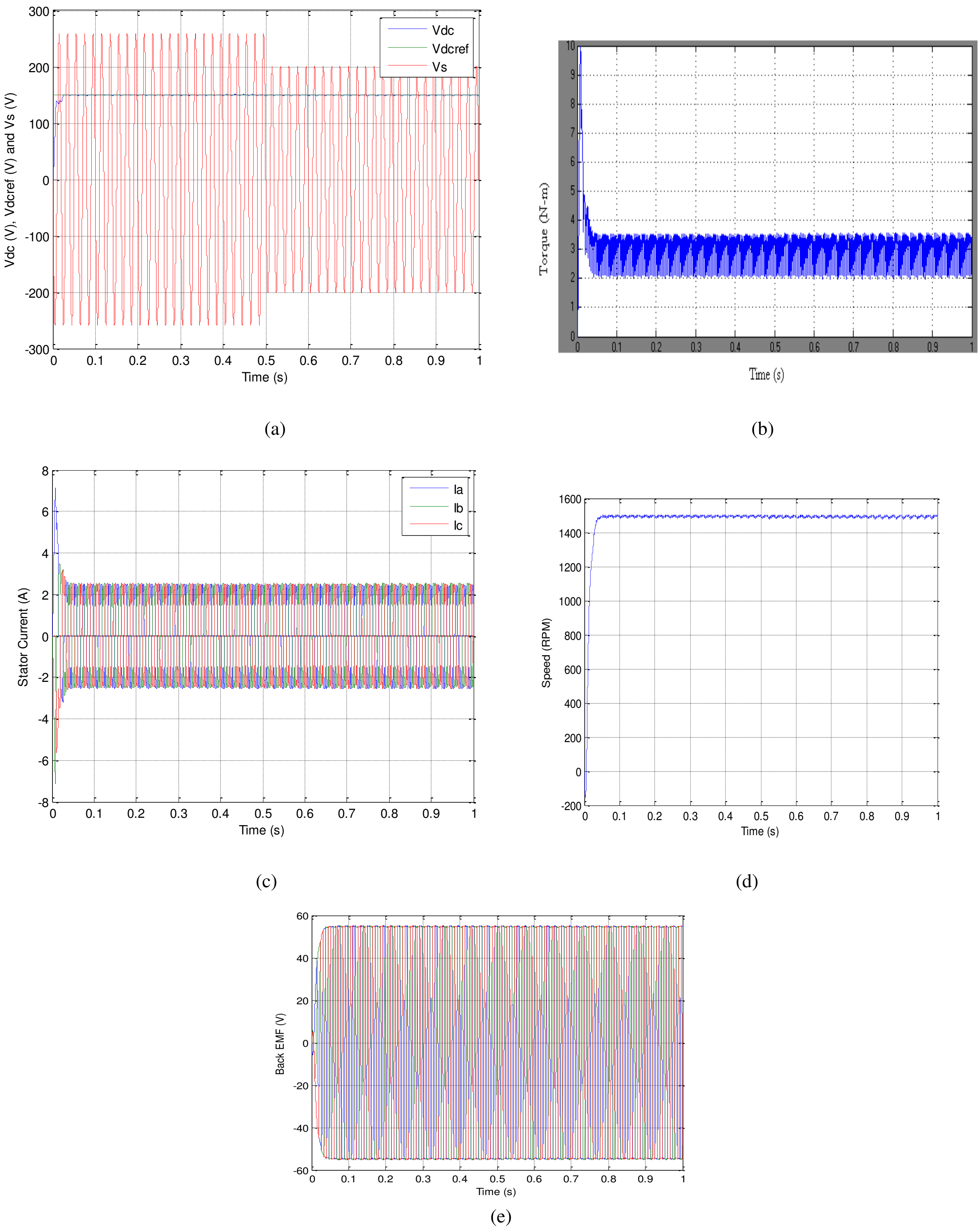

Fig. 9. Simulated responses of PFC BLBBR fed BLDC motor with FLC for source voltage change from 258V to 200V, (a) source voltage, measured and reference DC link voltage of the converter, (b) torque, and (c) stator currents, (d) speed and (e) back emf.

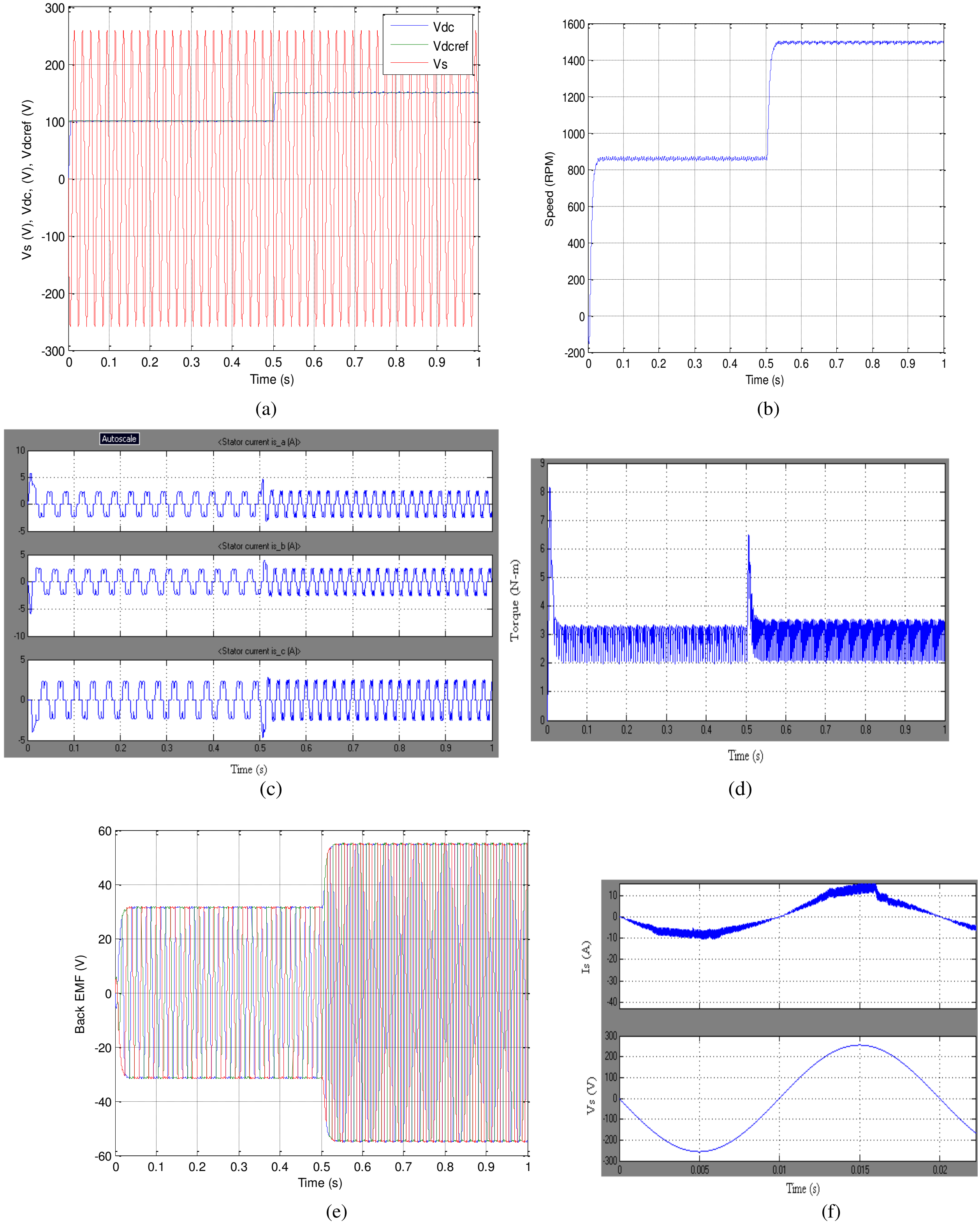

Fig. 10**.** Simulated responses of PFC BLBBR fed BLDC motor with FLC for step change reference DC link voltage from 100V to 150V, (a) source voltage, measured and reference DC link voltage of the converter, (b) speed, and (c) stator current, (d) torque, (e) back emf (f) source voltage and current.

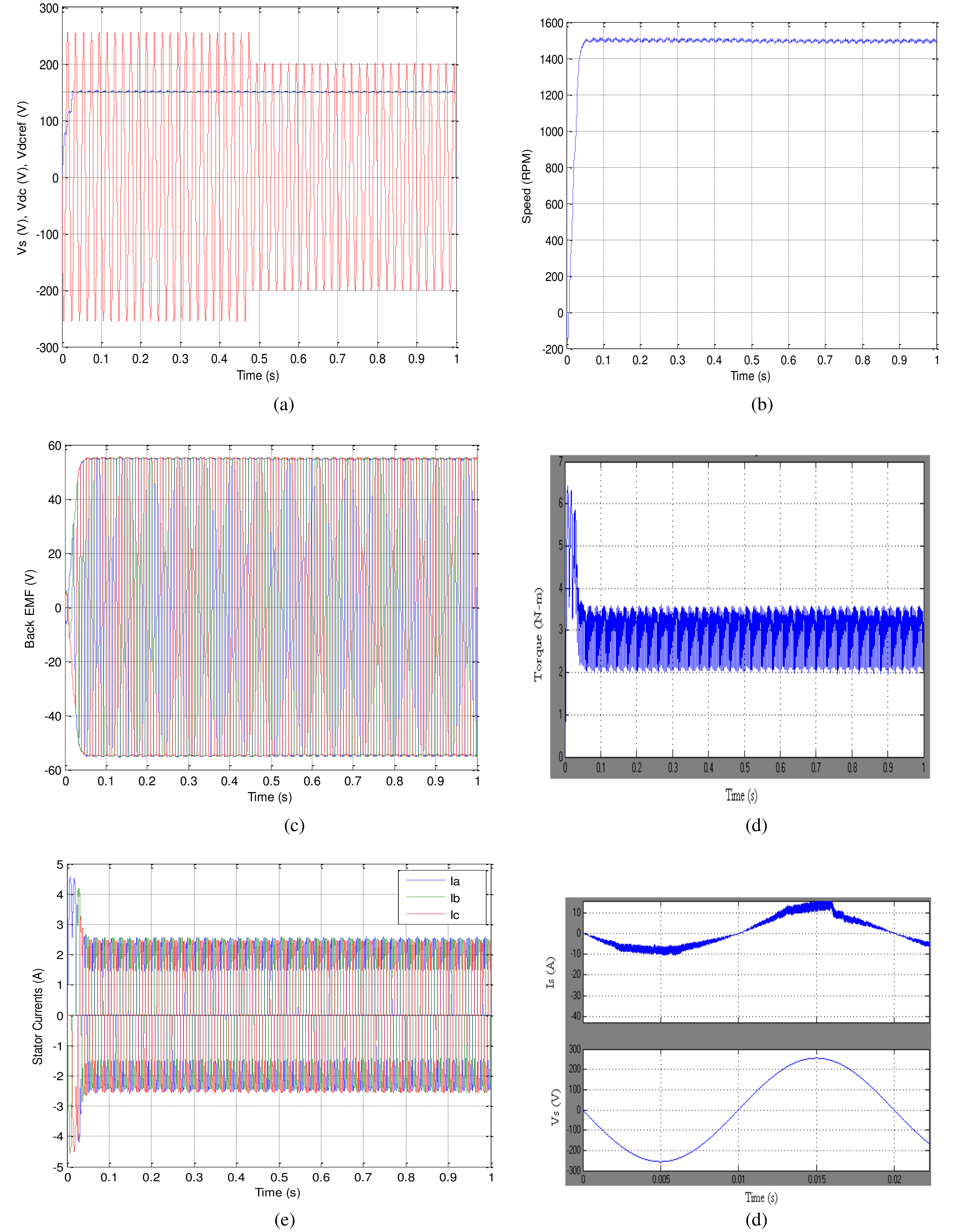

Fig. 11**.** Simulated responses of PFC BLBBR fed BLDC motor with PI controller for source voltage change from 258V to 200V, (a) source voltage, measured and reference DC link voltage of the converter, (b) speed, and (c) back emf, (d) torque and (e) stator currents, (d) supply voltage and current.

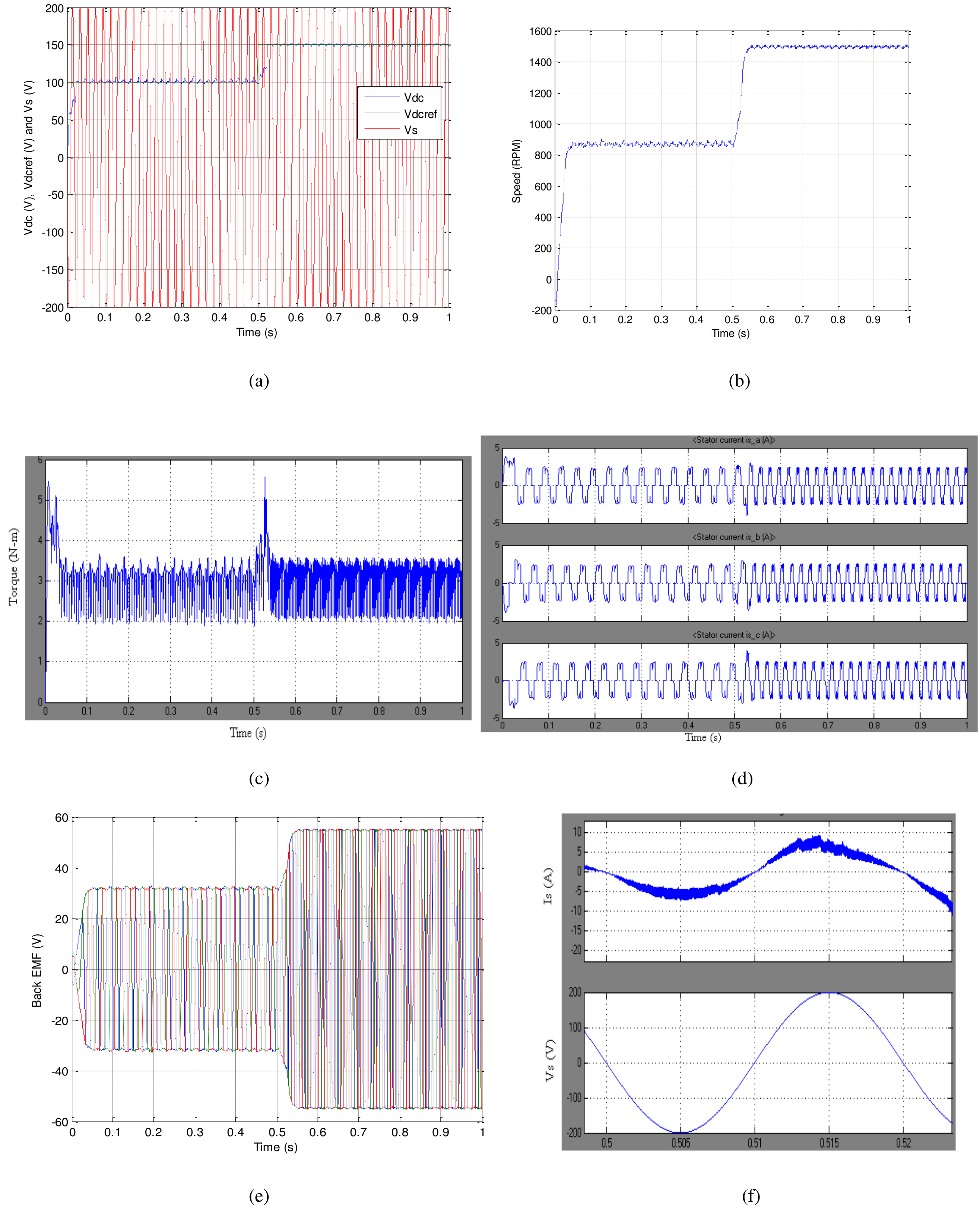

Fig. 12. Simulated responses of PFC BLBBR fed BLDC motor with PI controller for step change reference DC link voltage from 100V to 150V, (a) source voltage, measured and reference DC link voltage of the converter, (b) speed, and (c) torque, (d) stator currents, (e) back emf and (d) source voltage and current.

Figs. 7, 9 and 11 shows simulated results of the output voltage, source current, source voltage, reference voltage, speed, back emf, zoomed back emf, zoomed stator currents and stator currents of PFC BLBBR fed BLDC motor for step change DC link capacitor voltage from 100V to 150V at time of 0.5 s using NC, FLC and PI controller. From these results, it can be seen that the PFC converter and BLDC motor parameters using NC has produced negligible peak overshoots and settling time in comparisons with PI controller and FLC. Figs. 8, 10 and 12 show simulated results of the output voltage, reference voltage, source voltage, source current, speed, back emf, zoomed back emf, zoomed stator currents and stator currents of PFC BLBBR fed BLDC motor for source voltage change from 258V to 200V using NC, FLC and PI controller. Again, it can be seen that PFC BLBBR and BLDC motor parameters using NC has produced negligible peak overshoots and settling time in comparison with other controllers. Finally, the designed NC can be performed at any operating conditions over the other designed controllers for PFC BLBBR fed BLDC motor drive.

5. Conclusions

The design and implementation of ICs for variable speed PFC BLBBR operated in DCM fed BLDC motor drive without sensing the speed has been successfully demonstrated in computer simulation with help of MATLAB/Simulink model software platform. Several results are addressed to show the proficient of designed ICs. The PFC BLBBR fed BLDC using NC has produced high-quality output voltage regulation that can lead to excellent speed regulation, improved transient and dynamic characteristics during large line and load variations, and minimized THD that can lead to high power factor at A.C mains in comparison with FLC and PI controller. Therefore it is more suitable for drives, and LED drive and battery operated car etc.,

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