A novel hybrid-fuzzy logic based UVC technique for solar-PV/grid integrated water-pumping system

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ABSTRACT

The continual depletion of fossil fuels and increased green-house emissions are persuading the consumers to install micro-renewable energy sources-based water pumping system. Among numerous energy sources, the solar-PV plays a significant role in water pumping application due to its virtuous, environment friendly, noise-free and abundant nature, so on. Along with solar-PV, the grid integrated system enables the continuous operation of water pumping system during varying temperature and irradiance conditions, and also delivers available solar-PV energy to grid during non-functional of pumping system. The above operations are carried by using bidirectional inverter which is controlled by using unit-vector control (UVC) technique. It consists of proportional-integral controller, which is not suited for regulation of DC-link voltage at desired level because of improper selection of gain values. In this work, an intelligent hybrid-fuzzy logic based UVC technique evidences the intelligent knowledge base for better regulation of DC-link voltage and power-flow of bidirectional inverter. The performance and operation of proposed hybrid-fuzzy logic control UVC technique for solar-PV/Grid integrated water-pumping system is evaluated under various operating cases by using MATLAB/Simulink tool; simulated results are conferred with superlative comparisons.

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1. INTRODUCTION

Water resources are essential in daily human life for survival in a variety of applications. Approximately 85% of pure water reserves are utilized for drinking, irrigation, the farming industry, and other purposes. Because of increased food demand and population growth, the proportion of water used will fluctuate in the future. As a result, there is an urgent need to come up with novel approaches based on modern technology to facilitate the sustainable use of water resources [1]. The source of electricity used to lift water from rivers ponds, and canals is a critical issue in several developing nations. Traditional pumping systems uses diesel, which increase fuel costs, CO_2 emissions, environmental damage, and efficiency, among other things [2]–[6]. Generally, standalone pumping systems need an electric motor for lifting water from rivers lakes, or waterways and preserving it in a storage tank for later usage. The electrical motor is the most essential component in the pumping system [7]. In recent years, the permanent-magnet brushless DC motor (PMBLDC) has provided significant merits over AC or DC motors, including high efficiency, low maintenance, more power density, long life, reduced electromagnetic interference (EMI) loss, and so on [8]–[12]. The standalone solar PV system suffers significantly and fails to operate at its maximum rating when temperatures, irradiance levels, and climatic conditions may vary. The obtainable solar-PV energy is utilized for powering the PMBLDC motor via a DC-DC boost converter that is controlled by incremental-conductance maximum-power point tracking (INC-MPPT) which makes the PMBLDC motor is to be self-start drive. Furthermore, during the nighttime or when it is cloudy, the pumping system is under-utilized and is temporarily shut down or closed. The disadvantages of a standalone pumping system are minimized by using the battery energy, which is widely recognized as a backup option when unavailability of solar-PV system to create an efficient pumping system. However, it has inadequate transfer ability; it is costly, has a short life, and has a high-temperature sensibility when using battery energy as a backup solution [13]–[18].

On the other hand, a utility grid is used as backup energy in a solar-PV-operated PMBLDC motor-fed pumping system. This grid will supply the energy to PMBLDC motor, resulting in an uninterruptible pumping system and also delivering the full-capacity of water irrespective of operating conditions like cloudy or night conditions. The primary goal of this work is to establish a solar-PV/grid interface PMBLDC fed pumping system. When the solar-PV energy is available (constant or full radiation), no grid energy is utilized, and the solar PV will continually generate energy for running the pumping system. When pumping system is not in operational; but the solar-PV is in running condition, the generated power is distributed directly to utility-grid which is defined as power-supplied or generated mode. It gives extra income source to consumers, farmers by delivering available solar-power into utility-grid [19], [20].

Figure 1 shows the solar-PV/utility-grid integrated pumping system. It utilizes the bi-directional voltage-source converter (BVSC) for regulating the bi-directional power-flow by using unit-vector control (UVC) technique is proposed in [21]–[25]. This UVC technique regulates the power-flow along with maintaining DC-link voltage as constant by utilizes the proportional-integral (PI-UVC) control scheme. This traditional PI-UVC technique is not suitable for both bi-directional power-flow and regulating DC-link voltage at the desired level due to incorrect gain value selection. In this work, an intelligent hybrid-fuzzy logic (HFL) DC-link control of UVC technique evidences the intelligent knowledge base for better regulation of bi-directional power-flow and DC-link voltage. The performance and operation of proposed HFL-UVC control technique for solar-PV/grid integrated pumping system is evaluated under various operating cases by using MATLAB/Simulink tool; simulated results are conferred with superlative comparisons.

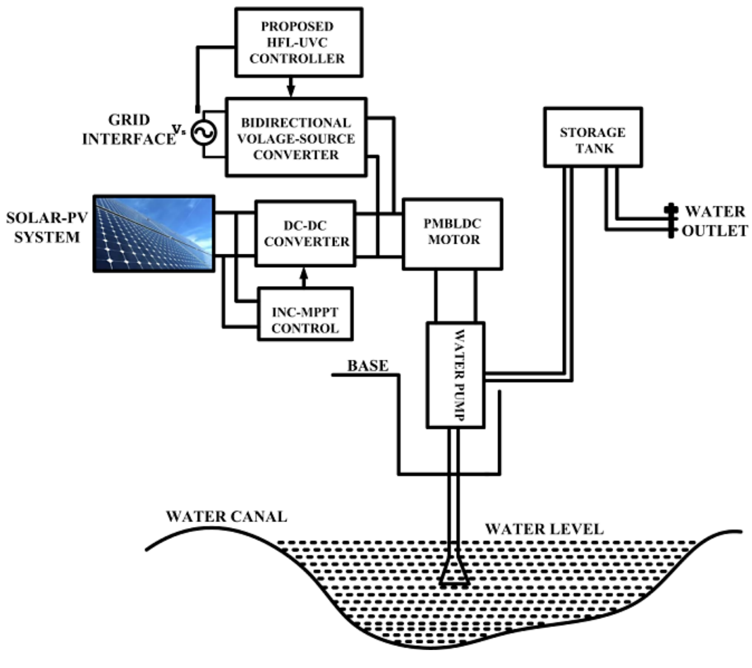


Figure 1. Solar-PV/grid integrated water pumping system

2. PROPOSED CONCEPT

The performance of proposed HFL-UVC technique controlled solar-PV/grid integrated PMBLDC driven pumping system has been analyzed in various operating conditions. In involves, i) only solar-PV is feeding the PMBLDC motor drive, ii) only grid is feeding the PMBLDC motor drive, iii) non-functional of pumping system, iv) dynamic transition applied between utility-grid to solar-PV feeding the PMBLDC motor drive, and v) dynamic transition applied between solar-PV to both grid/solar-PV feeding the PMBLDC motor drive as power sharing mode, respectively. In includes, solar-PV/grid energized PMBLDC motor driven water-pumping through BVSC followed by DC-DC converter. Similarly, the line-inductors of BVSC acts as second-order filter for counteracting the harmonic current distortions, improving the power-factor and attain enhanced power-quality features in grid system. The input DC voltage of BVSC is energized through utility-grid system transfers bi-directional power which is controlled by proposed HFL-UVC control technique.

In this HFL-UVC technique consists of single-phase phase-lock loop for synchronization of grid voltage with rated current. It generates the sinusoidal voltages in vector form at rated frequency and the amplitude of reference current ($I_{sa.ref}$) is obtained by differentiating the reference DC voltage ($V_{dca.ref}$) and measured DC voltage (V_{dca}). When it differentiates, an error has been attained which is reduced through traditional PI controller with 't' time instants.

$$V_{er}(t) = V^{*}_{dca.\mathrm{ref}}(t) - V_{dca}(t) \tag{1}$$

$$I_{sa.er}(t) = V_{er}(t-1) + K_p\big(V_{er}(t) - V_{er}(t-1)\big) + K_i V_{er}(t) \tag{2}$$

The significance of an intelligent hybrid-fuzzy logic (HFL) controller is creation of symbolic inference system with prominent knowledge base. This HFL controller exemplifies the intelligent knowledge-based process with the combination of PI controller, which included FL-Membership functions and a HFL-rule base. Figure 2 shows the block diagram of HFL control scheme. These HFL-membership functions and HFL-rules are key components in HFL controller by incorporating significant human knowledge into an artificial knowledge base. Several attempts have been made to interpret the necessary enhancement in system performance by incorporating the superior learning technique to commute the HFL-rules and HFL-membership functions. The HFL-rule base is the heart of HFL control and the gathering of necessary information for depicting data manipulation values, linguistic models, and HFL-rule characterization, among other things.

$$e(s) = V^{*}_{dc.r} - V_{dc.a} \tag{3}$$

$$\Delta e(s) = e(s) - e(s-1) \tag{4}$$

Where, $e(s)$ and $\Delta e(s)$ are the error and change in error.

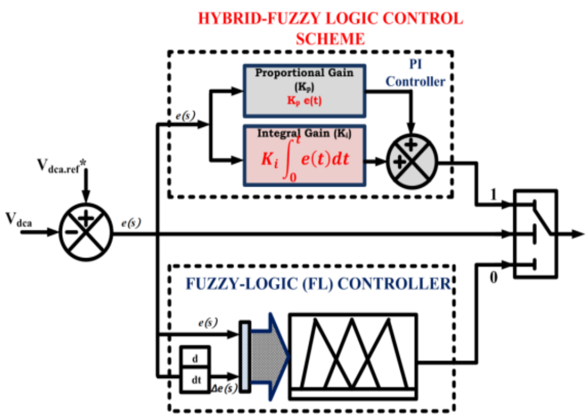


Figure 2. Block diagram of HFL controller

For feasible combinations obtained from HFL-input data, a look-up table related to discrete universes representation of HFL control outcome is developed. The fuzzy inference system provides information on how the FL controller performs certain logical operations in conjunction with the knowledge base as "IF, and Then" from various linguistic logic functions. The HFL controller has a high robust performance, is model free, has a high strength index, and is operated as a subjective decision based on a universe-approximation technique with a HFL-rule base algorithm. The related HFL-membership functions and HFL-rule base is clearly depicted in Figure 3 and Table 1. The reference fundamental current ($I_{sa.ref}$) is generated by a HFL-UVC technique from grid-voltage, which extracts the phase-angle and shape of the grid-voltage and it is multiplied with extracted current for generation of feasible reference current as shown in (5) and (6).

$$I_{sh}\,(t) = \left|\frac{U_{v,c}(t)}{U_{p,c}}\right| \tag{5}$$

$$I^{*}_{sa.ref}(t) = I_{sa.err}(t)\; \times I_{sh}(t) \tag{6}$$

Finally, the reference current is compared with measured actual current for getting feasible switching states to BVSC through hysteresis current controller (HCC). The schematic diagram of proposed HFL-UVC technique controlled solar-PV/Grid integrated PMBLDC drive fed pumping system is depicted in Figure 4. The system parameters and values of proposed scheme are presented in Table 2.

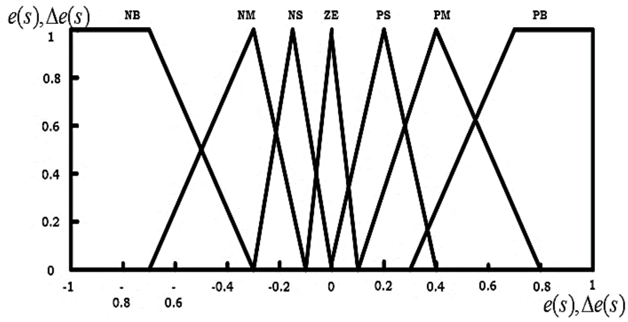


Figure 3. HFL membership functions

Table 1. HFL-rule-base

$e\,(s)$ / $\Delta e\,(s)$	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	NM	NS	ZE	PS	PM	PB

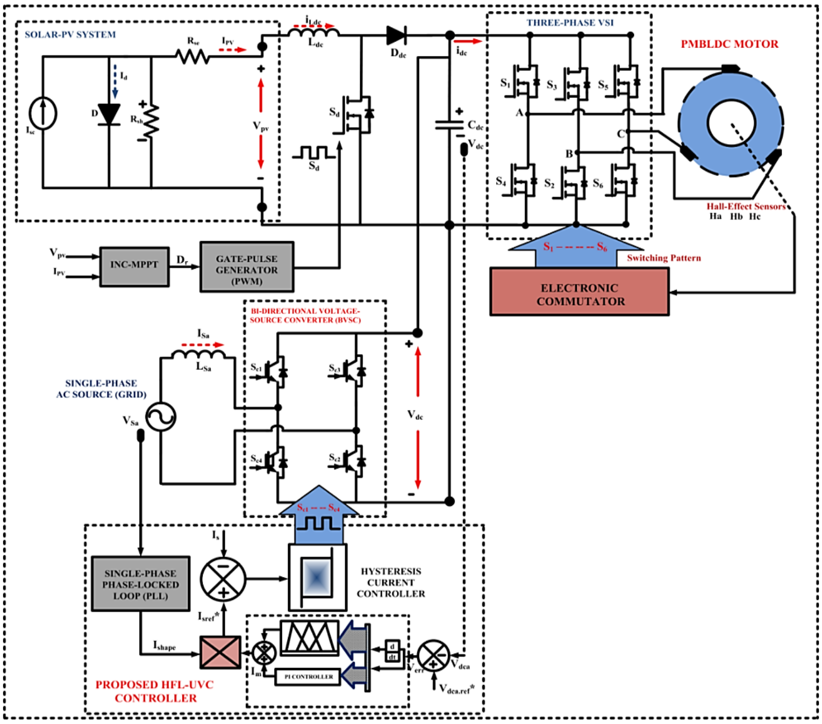


Figure 4. Schematic diagram

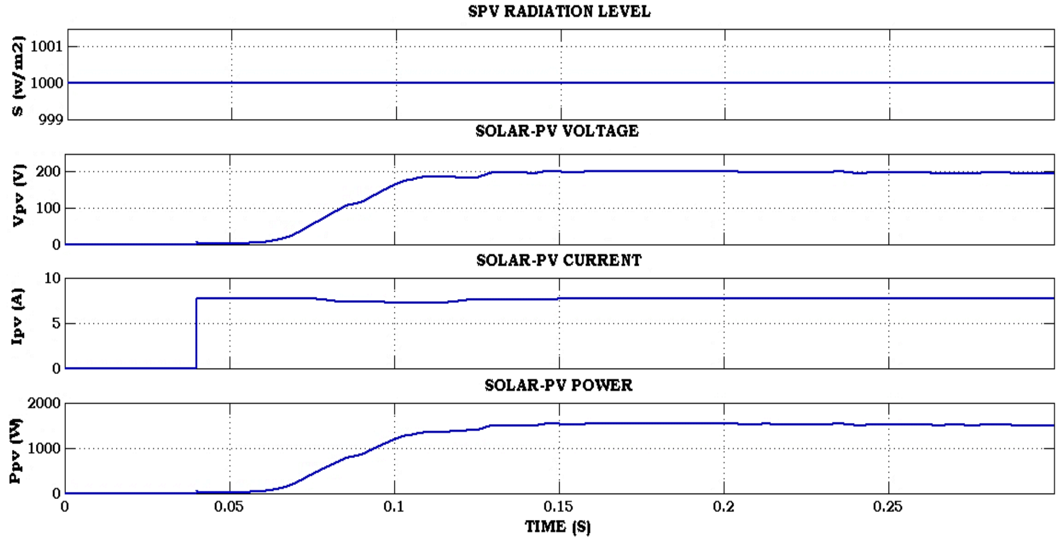
Table 2. System parameters and values

S.No	System specifications	Values
1	Solar-PV	V_{pv}-200 V, I_{pv}-7.5 A, P_{pv}-1.5 KW
2	Grid system	V_s-230 V_{rms}, F_s-50 Hz
3	DC-link capacitor	V_{dc}-270 V, C_{dc}-1010 µF
4	PMBLDC motor	R_s-3.58 Ω; L_s-9.13 mH, N_r-3000 rpm, V_b-270 V
5	Switching frequency	F_s-5 KHz

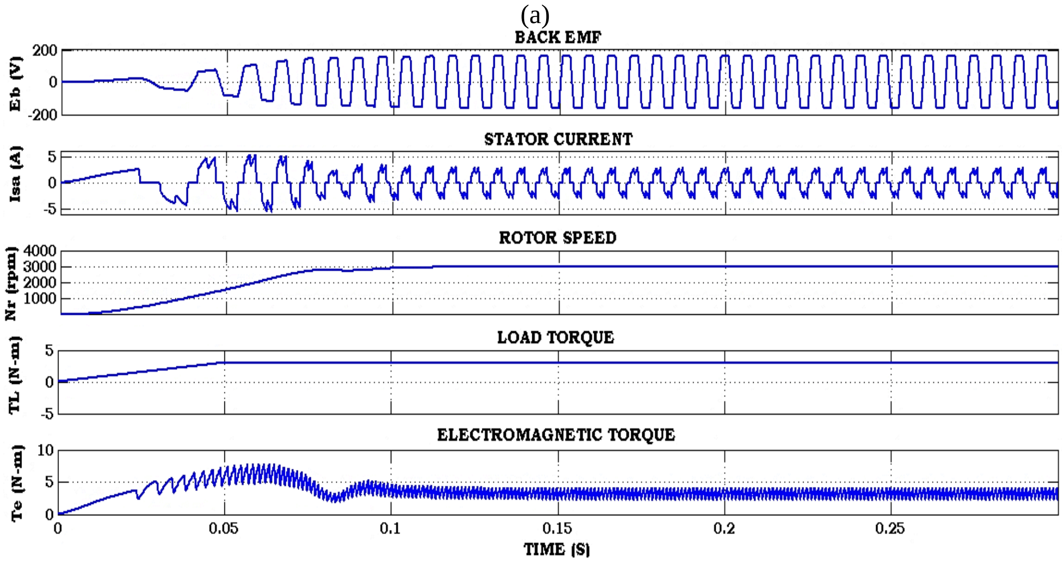
3. RESULTS & DISCUSSION

3.1. Performance of only solar-PV feeds PMBLDC drive under starting and steady-state condition

Figure 5 shows the simulated results of when only solar-PV feeds PMBLDC drive under starting and steady-state condition. In this case, the solar-PV is only operated at its rated power when constant irradiance of S-1000 W/m^2. At starting and steady-state condition, the solar-PV produces the PV voltage of 200 V with a PV current of nearly 7.5 A attains the maximum solar-PV power of 1.5 KW as shown in Figure 5(a). Based on, obtained solar-PV power feeds the PMBLDC rotated at its rated speed of 3000 rpm, with stator current of 4.5 A and the trapezoidal back emf of 200 V, respectively as shown in Figure 5(b). During steady-state condition, the electromagnetic torque reaches the load torque with a value of 5 Nm which defines the PMBLDC motor has been self-started.



(a)

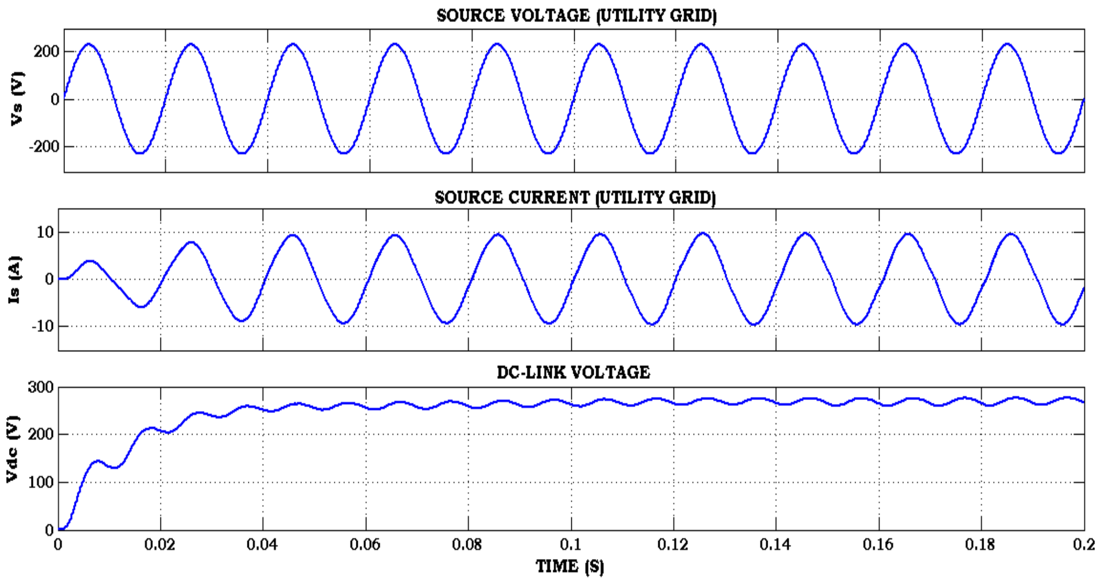


(b)

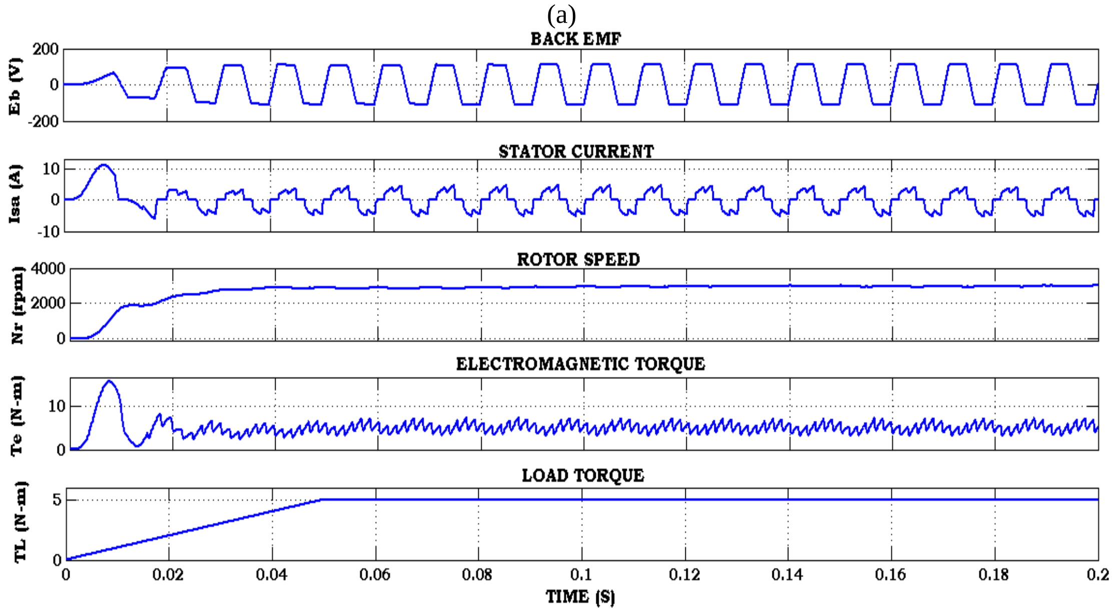
Figure 5. Simulation results of only solar-PV feeds PMBLDC drive under starting and steady-state condition (a) solar-PV results and (b) PMBLDC drive results

3.2. Performance of only single-phase grid feeds PMBLDC drive

Figure 6 shows the simulated results of when only single-phase grid feeds PMBLDC drive under running condition. In this case, the only single-phase grid feeds the PMBLDC motor drive due to nighttime or bad-climatic conditions. The single-phase grid supplies the required energy to energize the PMBLDC drive with a voltage of 230 V, rated current of 10 A and DC voltage is maintained as constant with a value of 270 V is shown in Figure 6(a). Based on, obtained grid power feeding the PMBLDC rotated at rated speed of 3000 rpm, with stator current of 4.5 A and the trapezoidal back emf of 200 V, respectively as shown in Figure 6(b).



(a)

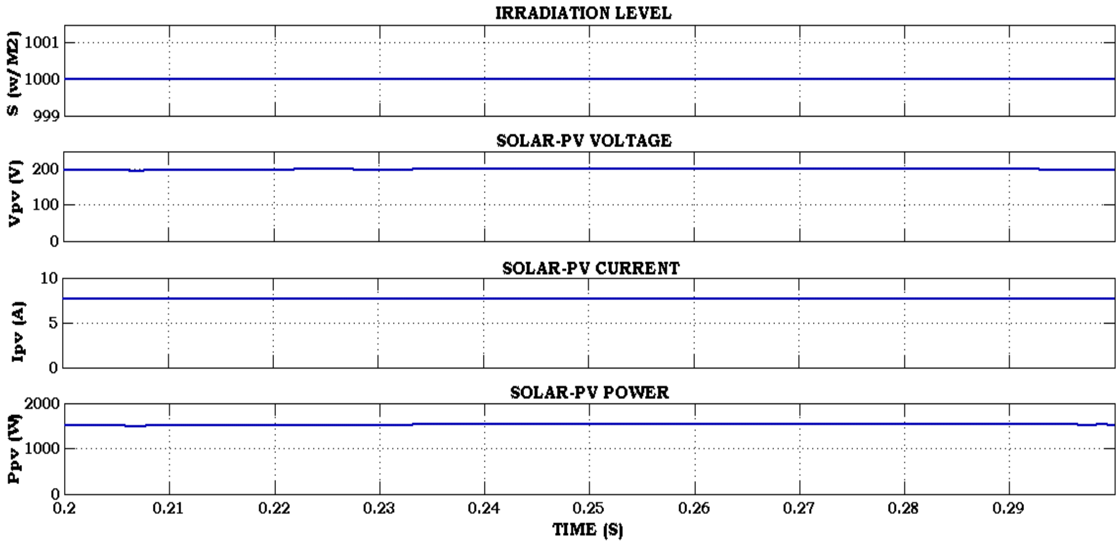


(b)

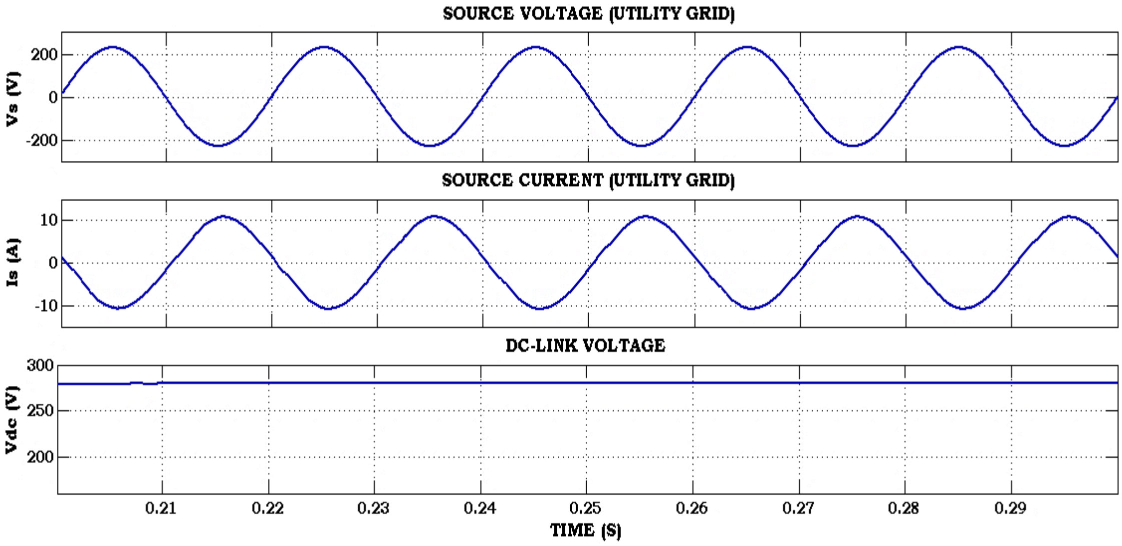
Figure 6. Simulation results of only single-phase grid feeds PMBLDC drive (a) utility-grid results and (b) PMBLDC drive results

3.3. Performance of solar-PV/grid integrated PMBLDC drive during non-functionality of water-pumping system

Figure 7 shows the performance of solar-PV/grid integrated PMBLDC drive during non-functionality of water-pumping system. In this case, PMBLDC motor fed pumping system is not operated because of storage-tank was full. Then, the obtained solar-PV power is directly feeds the single-phase grid system and produces the PV peak voltage of 200 V with a PV current of nearly 7.5 A delivers the maximum solar-PV power of 1.5 KW as shown in Figure 7(a). As well as, the single-phase grid receives the obtained solar-PV power with a voltage of 230 V, rated current of 10 A, respectively. The grid current is out-of phase with grid voltage represents the solar-PV feeding the grid and producing reverse power-flow of BVSC and the DC voltage is maintained as constant of 270 V is shown in Figure 7(b).



(a)

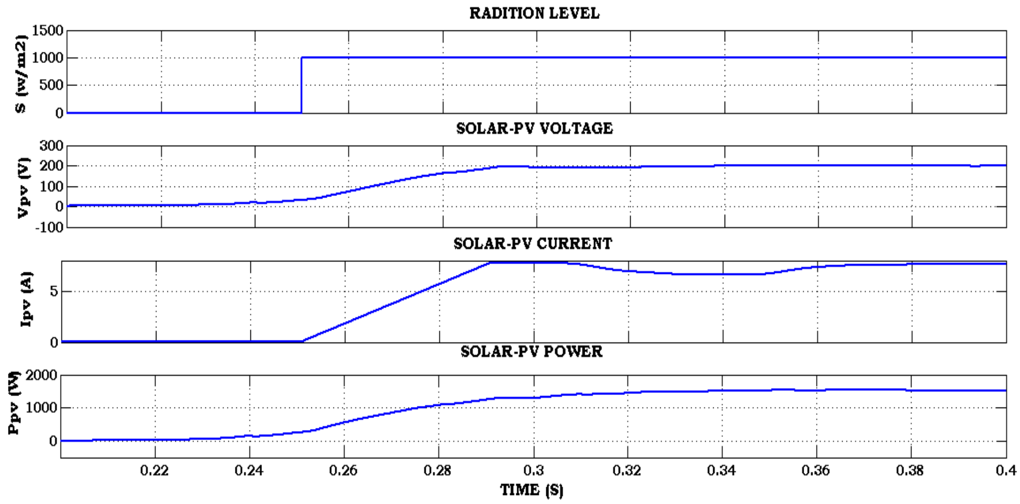


(b)

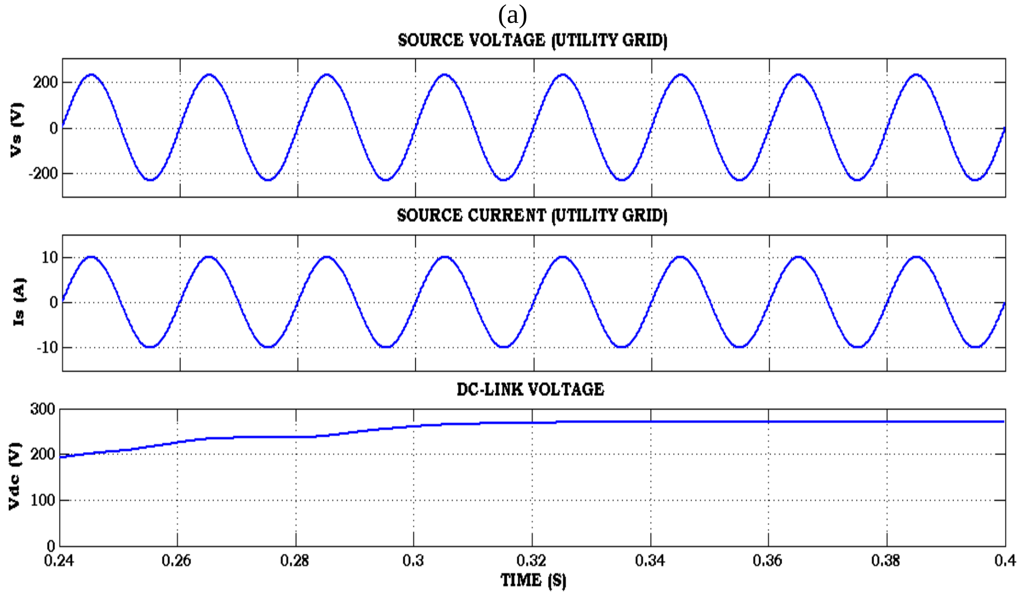
Figure 7. Performance of solar-PV/grid integrated PMBLDC drive during non-functionality of water-pumping system (a) solar-PV results and (b) utility-grid results

3.4. Dynamic transition between grid integration to solar-PV feeding PMBLDC motor drive

Figure 8 shows dynamic transition between grid integration to solar-PV feeds the PMBLDC drive. In this case, initially pumping system is operated by single-phase grid because of solar-PV is not operated due to nighttime or cloudy condition before time instant t-0.25 sec. The solar-PV results are depicted in Figure 8(a), it represents the sudden integration of utility-grid supplying energy to pumping system. Moreover, the direction of grid current is in reverse direction within the period of half-cycle and also maintaining DC voltage as constant with a value of 270 V as depicted in Figure 8(b). Afterwards time t-0.25 sec, the available solar-PV power feeds the pumping system and comes to standalone mode is depicted in Figure 8(c).



(a)



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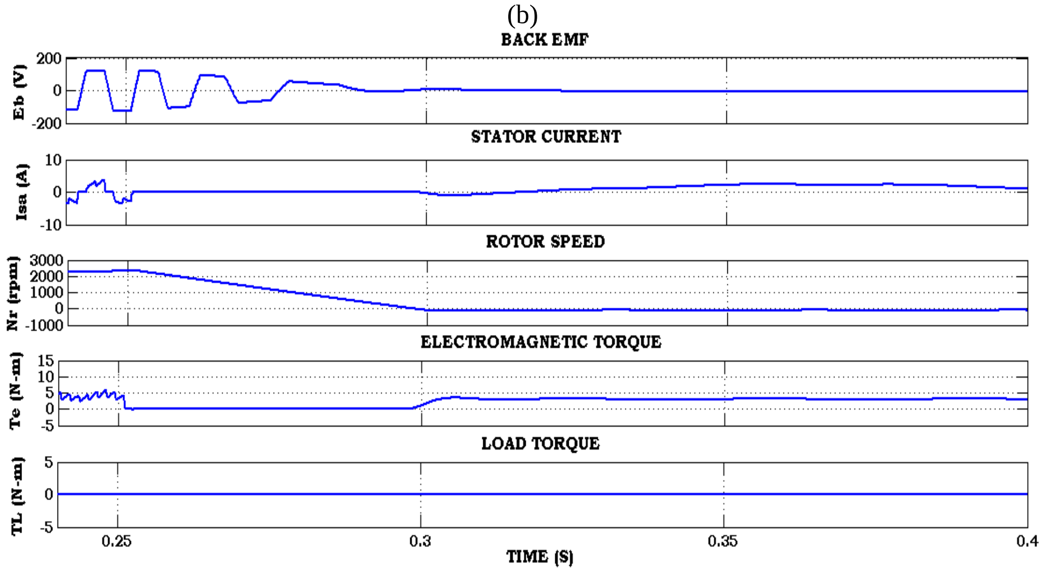


(c)

Figure 8. Results of dynamic transition between the grid integration to solar-PV feeding PMBLDC motor drive (a) solar-PV results, (b) utility-grid results, and (c) PMBLDC drive results

3.5. Dynamic transition between solar-PV to both grid/solar-PV feeding PMBLDC motor drive under power-sharing mode

Figure 9 (see Appendix) shows the results of dynamic transition between solar-PV to both grid/solar-PV feeds PMBLDC drive under power-sharing mode. In this case, initially solar-PV is solely feeding the requisite rated energy to PMBLDC motor for driving the pumping system. Due to sudden variations in irradiance, the irradiance suddenly changes from S-1000 W/m^2 to S-500 W/m^2 at a time of t-0.25 sec, at this time period the solar-PV is not able to feed the rated capacity of PMBLDC motor. During this period, the grid delivers required energy to PMBLDC drive is shown in Figure 9(a), and before t-0.25 sec no power consumption from grid is shown in Figure 9(b). After time t-0.25 sec, the required power is delivered by grid producing the current of nearly 4.5 A which shows the in-phase with voltage of 230 V and maintains DC voltage is maintained as constant of 270 V, respectively. Based on, obtained grid power feeding the PMBLDC is rotated at its rated speed of 3000 rpm, with stator current of 4.5A and the trapezoidal back emf of 200 V, the electromagnetic torque reaches the load torque with a value of 5 Nm respectively as shown in Figure 9(c). The total harmonic distortion (THD) value of grid current while using traditional PI-UVC, FL-UVC and proposed HFL-UVC techniques are measured with a value of 3.87%, 2.05%, 1.59%, respectively is shown in Figure 9 (d)-(f). The THD of grid current in proposed HFL-UVC technique is well within IEEE-519/2014 standards. THD comparison and graphical view of grid currents in traditional PI-UVC, FL-UVC, and proposed HFL-UVC techniques fed PMBLDC motor drive is illustrated in Table 3 and Figure 10.

Figure 11 shows the rotor speed of PMBLDC motor in traditional PI-UVC, FL-UVC, and proposed HFL-UVC techniques, the time domain specifications of PMBLDC motor in traditional PI-UVC, FL-UVC, and proposed HFL-UVC techniques is illustrated in Table 4. It represents the proposed HFL-UVC technique requires very low delay-time, less rise-time/peak time, low peak-overshoots and reduced settling time over the traditional PI-UVC and FL-UVC techniques. The proposed HFL-UVC techniques recommends the highly stability performance under various operating conditions in solar-PV/grid integrated pumping system.

Table 3. THD comparison of grid currents in traditional PI-UVC, FL-UVC, and proposed HFL-UVC techniques fed PMBLDC motor drive

THD (%)	Grid Current
PI-UVC Technique	3.87%
FL-UVC Technique	2.05%
Proposed HFL-UVC Technique	1.59%

Table 4. Time domain specifications of PMBLDC motor in traditional PI-UVC, FL-UVC, and proposed HFL-UVC techniques

Domain Specifications	Delay Time (t_d) in sec	Rise Time (t_r) in sec	Peak Time (t_p) in sec	% Peak Overshoot (%)	Settling Time for (t_s) in sec
PI-UVC Technique	0.058 s	0.079 s	0.088 s	3%	0.14 s
FL-UVC Technique	0.009 s	0.03 s	0.048 s	1.25%	0.052 s
Proposed HFL-UVC Technique	0.003 s	0.01 s	0.018 s	0.5%	0.023 s

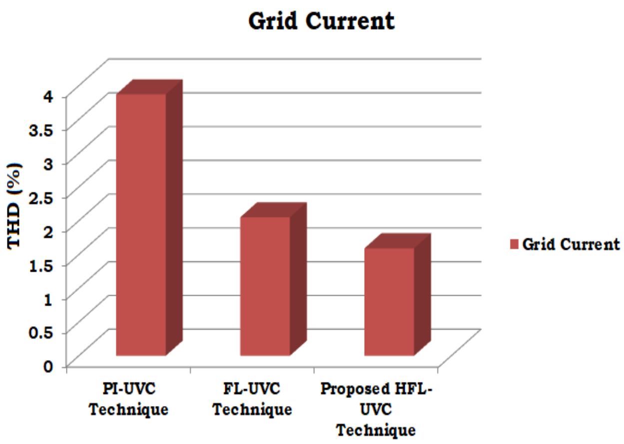


Figure 10. Graphical view of grid currents in traditional PI-UVC, FL-UVC, and proposed HFL-UVC techniques fed PMBLDC motor drive

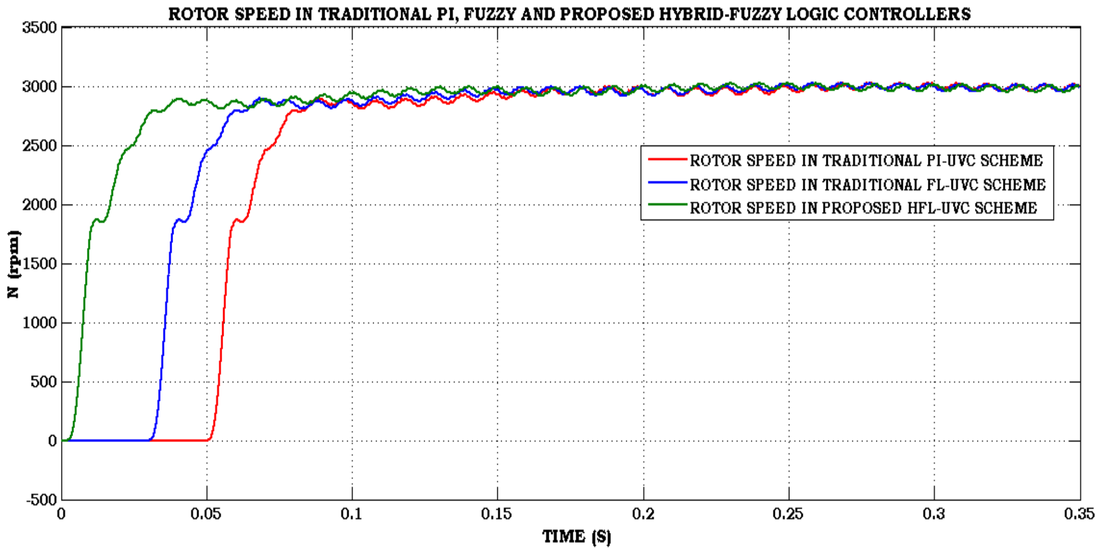


Figure 11. Rotor speed of PMBLDC motor in traditional PI-UVC, FL-UVC, and proposed HFL-UVC techniques

4. CONCLUSION

The efficient design and performance of proposed HFL-UVC controlled solar-PV/grid integrated PMBLDC motor drive fed water pumping system has been validated under several operating conditions. The proposed HFL-UVC regulates the bidirectional power-flow and also maintaining the constant DC voltage enables the flexible utilization of solar-PV or grid energy to make continuous functioning of pumping system under cloudy or bad-weather conditions. Along with feasible operating functions, the HFL-UVC technique enhances the THD profile of grid current and it is well within IEEE-519/2014 standards. By using the proposed HFL-UVC technique, attains very low delay-time, less rise-time/peak time, low peak-overshoots and reduced settling time over the traditional PI-UVC and FL-UVC techniques. When pumping system is not in operational; but the solar-PV is in running condition, the generated power is distributed directly to utility-grid which gives extra income source to consumers, farmers by delivering available solar-power into utility-grid.

APPENDIX

(a)

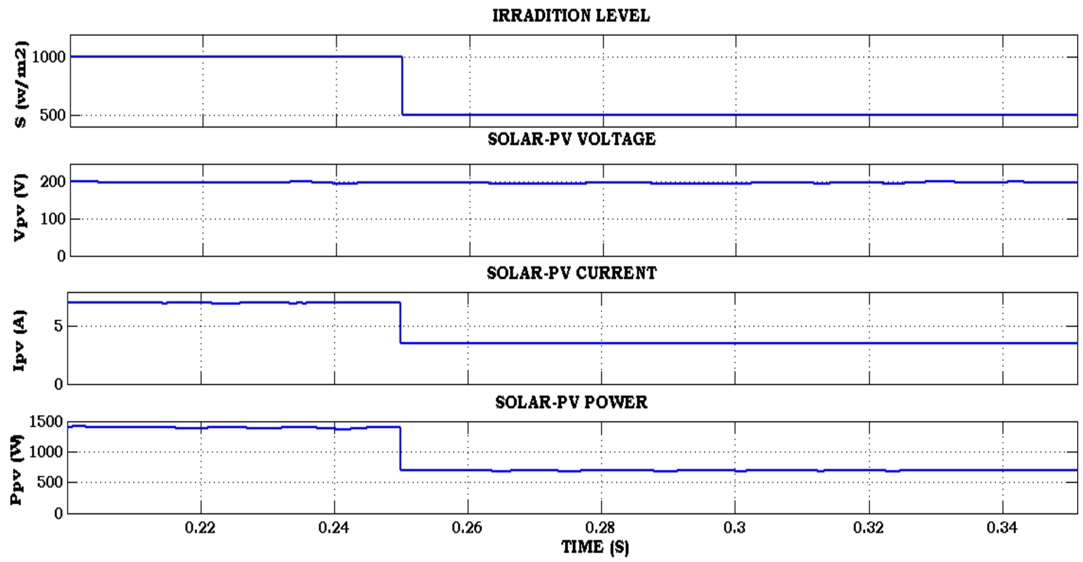


Figure 9. Results of dynamic transition between solar-PV to both grid/solar-PV feeding PMBLDC motor drive under power-sharing mode: (a) solar-PV results

(b) (c) (d)

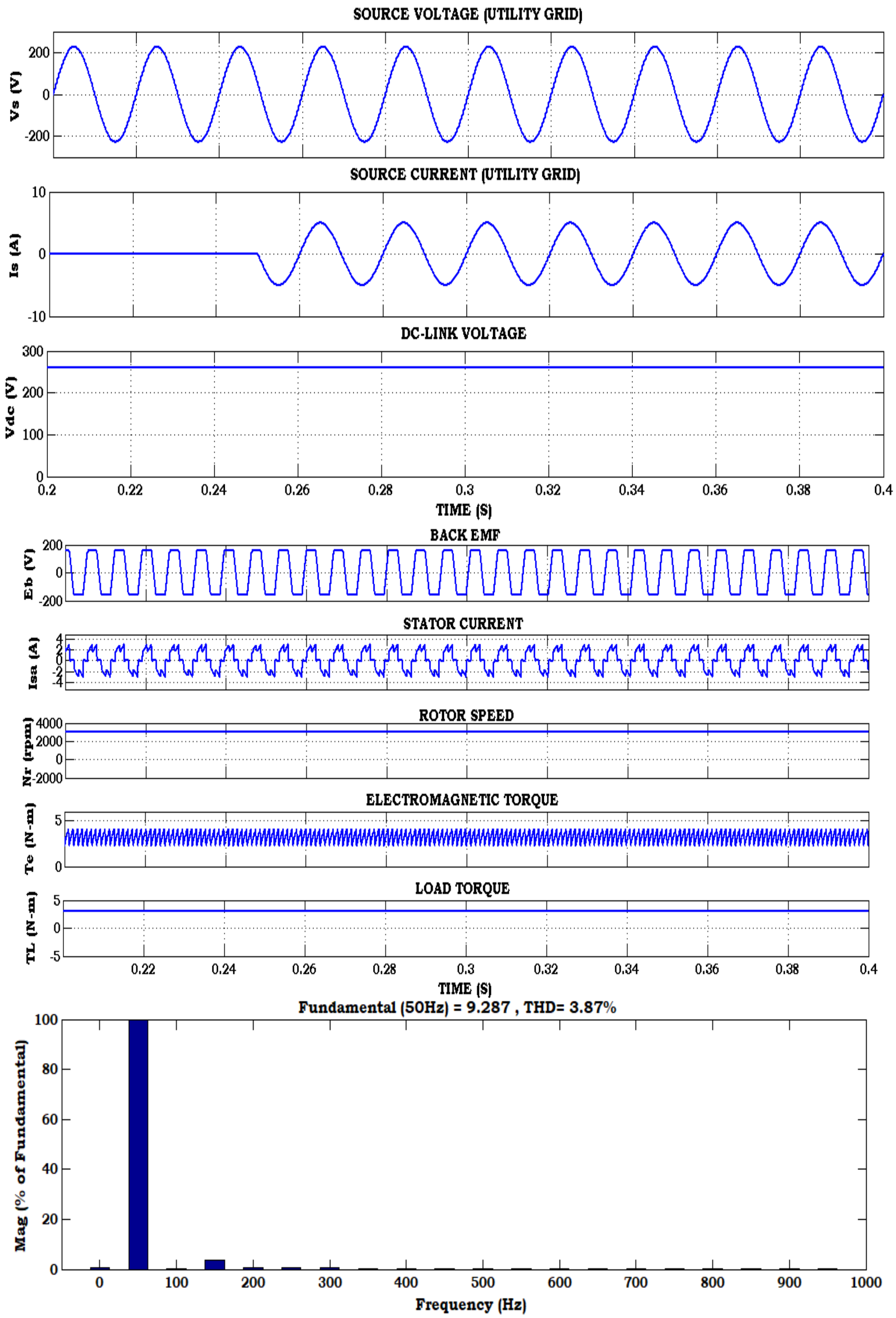
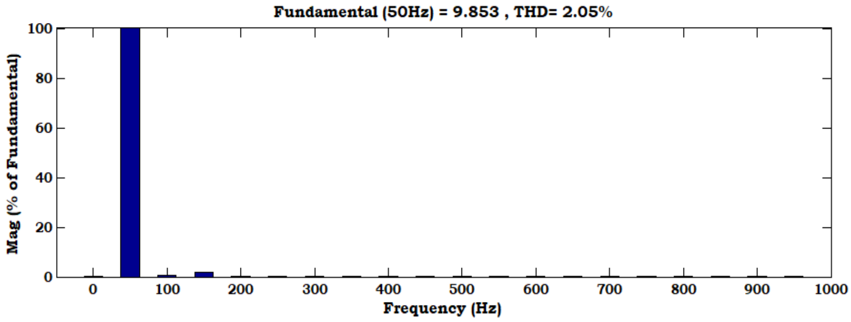


Figure 9. Results of dynamic transition between solar-PV to both grid/solar-PV feeding PMBLDC motor drive under power-sharing mode: (b) utility-grid results, (c) PMBLDC drive results, and (d) grid current THD in traditional PI-UVC (continued)

(e)



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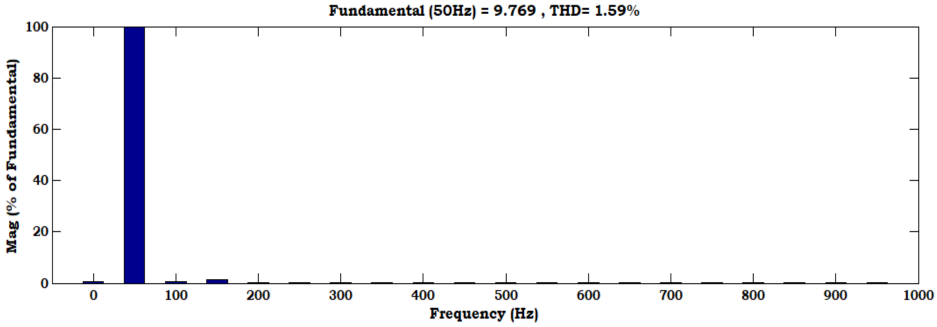

Figure 9. Results of dynamic transition between solar-PV to both grid/solar-PV feeding PMBLDC motor drive under power-sharing mode: (e) grid current THD in traditional FL-UVC and (f) grid current THD in proposed HFL-UVC (continued)

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