A RCC MPPT based open-end winding induction motor drive for pumping applications

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Abstract

An open end winding induction motor (OEWIM) presents an integrated solution for a photovoltaic (PV) fed water-pump drive system. The dual-inverter-fed OEWIM drive achieves the functionality of a three-level inverter and requires low worth dc-bus voltage. This helps in an optimal arrangement of PV modules, which could avoid large strings and helps in refining the PV performance with wide bandwidth of operating voltage which in turn decreases the voltage rating of the dc-join capacitors and switching devices incorporated in the system. The proposed control system accomplishes a summation of both maximum power point tracking (MPPT) followed by V/f control for the productive usage of the PV boards and the machine. Proposed method is implemented by using RIPPLE correlation control. The proposed control plan requires the detecting of PV voltage and current as it were. By implementing this technique number of sensors required is less. All the simulation results of this work under various natural conditions are presented in this paper.

Keywords: centrifugal pump; dual-inverter; maximum power point tracking (MPPT); open-end winding induction motor (OEWIM); photovoltaic (PV) cell

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Introduction

More than 40% of aggregate electric force is devoured by the electrical engines (Maheswaran et al., 2012). Modernizations of human culture and developing uses of electric engines have exponentially expanded the interest for electrical vitality. This strengths and expansion in the force era limit. Be that as it may, because of environmental concerns, limitation and requirements are forced on expanding the era limit of traditional sources. Along these lines, contemporary exploration is engaged toward a viable usage of nonconventional vitality sources. Among the accessible nonconventional sources, photovoltaic (PV) innovation is by all accounts the most encouraging and appealing. This can be credited to declining expense of PV modules, free vitality source, zero upkeep, and clamor free operation. Hence, livelihood of a PV hotspot for controlling electric engine could be a decent arrangement particularly for water-pumps, electric fans, submersible pumps, and so forth. Such loads can have the alternative of ideally utilizing PV power at whatever point Sun force is accessible (Yao et al., 1994).
Further, when such loads are utilized as a part of the stand-alone system like water pumping application in household, farming, and mechanical areas, sun oriented PV fueled framework could be a decent arrangement. It could meet the necessity amid basic circumstance (i.e.) amid summer particularly in tropical nations like India. This empowers the utilization of electric engine pump with better execution and proficiency with the PV framework (Mapurunga et al., 2014). Some conceivable arrangements given for PV-nourished water-pump depended on use of dc engine either straightforwardly coupled (Appelbaum, 1986) or by means of a DC-DC converter (Alghuwaineum, 1992) with the PV source. Be that as it may, the prerequisite of consistent upkeep and higher expense limits the utilization of DC engines for their application in PV water pumping frameworks (Mapurunga et al., 2014). In this manner, there is a need of such an answer, to the point that uses the PV control adequately, while utilizing a minimal effort, low upkeep, solid, and strong engine for pumping application. The most appropriate engine for such an application is an impelling engine (IM).

The vast majority of them have utilized a dc–dc help converter as a part of the principal stage and the second stage involves a DC-AC inverter. Help converter increases and works the low esteem PV information voltage close most extreme force point (MPP) while the inverter gives the required air conditioning voltage to the IM. Additionally, the control strategies depend on either autonomous recurrence control, or a V/f control (Bhat et al., 1987). A common place PV pumping framework with two force molding stage as talked about before, this framework results in poor execution and lesser effectiveness. Subsequently, a solitary stage framework with easier control could be a superior decision (Jain et al., 2007; Danyali et al., 2014). One of such a framework was proposed by (Muljadi, 1997), in which the creators have utilized a six stage semi square wave inverter, which can deal with dc–ac reversal and in addition most extreme force point following (MPPT) for the PV source. It likewise requires channels, which are massive and costly. Further, this framework requires a higher voltage rating for the information dc-join capacitor and semiconductor gadgets. All these may build the cost, weight, size, and power loss of the framework.

While this framework results in low engine misfortunes, it is more mind boggling with more number of control variables and sensors. It is likewise a solitary stage framework, wherein the creators have proposed MPPT swell relationship control and least misfortunes point following strategies for control. Be that as it may, this framework requires more number of sensors, and results in low transmission capacity for PV working voltage. In this way, from the past examination, it is obvious there is a prerequisite for an ease, low-voltage single-stage force change PV water pumping framework with wide data transfer capacity of PV working voltage. Additionally, the three-level/multilevel inverter with a low dc-transport voltage could be a superior arrangement as the execution of this framework enhances with the expanded number of levels/ventures in the inverter yield voltage. Aside from high dependability and repetition, OEWIM has numerous great elements as
examined in the following passage. A Standout amongst the most imperative component of OEWIM is it utilizes two-level voltage-source inverters (VSIs) to accomplish three-level reversal. It likewise brings down voltage rating of semiconductor gadgets and info dc-transport electrolytic capacitor. This can be credited to the way that DC-transport voltage is planned in view of most extreme estimation of stage voltage rather than line-to-line voltage.

Dissimilar to the customary three-stage unbiased point-braced three-level inverter, wherein the DC-join capacitor is compelled to convey load current prompting substantial changes of voltage of the dc-nonpartisan point, the DC-join capacitor of OEWIM conveys just the swell current, along these lines coming about an irrelevant voltage variances. In this manner, OEWIM combined with the PV source could be a decent suggestion. This paper presents one such answer for a basic water-pump application. The proposed framework has the accompanying elements: It is a sparing framework as it uses a solitary force molding stage; It has inborn low dc-transport voltage necessity with V/f control coordinated with MPPT and utilizations three-level (DC-AC) reversal for better execution of engine; Low information dc-transport voltage necessity lessens the voltage rating of DC-connection capacitor and expansions transmission capacity of PV working voltage, it likewise decreases the voltage rating of the semiconductor gadgets utilized as a part of the inverter; It ideally utilizes the PV hotspot for every single ecological condition by working it at MPP, likewise, it utilizes V/f control coordinated in the MPPT calculation which enhances the execution of the engine and requires less number of sensors for its operation; three-level yield with the decoupled test arrived at the midpoint of zero-arrangement end (DSAZE) calculation further enhances the execution with lessened engine current swell. Rest of this paper is separated into four areas. Area II gives points of interest of demonstrating of the proposed framework. Area III portrays the operation and investigation of the proposed framework. Area IV depicts the control system and calculation proposed. Area V portrays the reproduction and trial results got. It additionally gives the nitty gritty cost investigation and correlation for the proposed framework with the current system(s).

**Modeling of the proposed system**

A proposed configuration of the solar PV-powered pumping system is shown in figure 1, which comprises of: 1) solar PV array; 2) dual-inverter namely Inverters I and II; 3) three-phase OEWIM with pump load; and 4) controller block which consists of MPPT and DSAZE PWM algorithm. These components are described in detail in the following sections.

**Photo Voltaic Source Model**

The PV source was modeled by using PV cell current-voltage characteristic equation as follows:

\[ i_{\text{pv cell}} = i_L - i_0 \left( e^{\frac{V_{\text{pv cell}}}{nRT}} - 1 \right) \]  \hspace{1cm} (1)

Where,

- \( i_{\text{pv cell}} \): PV cell current; \( i_L \): photo-current; \( i_0 \): Diode saturation current; \( n \): Diode quality or ideality factor; \( k \): Boltzmann constant; \( q \): electron charge; \( T \): panel operating temperature in Kelvin; \( R_s \): PV cell series resistance; \( V_{\text{pv cell}} \): PV cell voltage (V). The output of PV source is connected to inverter with DC bus
capacitance $C_{pv}$. By applying KCL at input of inverter (from Fig. 1)

\[ i_{pv} = i_c + i_{inv} = C_{pv} \frac{dV_{pv}}{dt} + i_{inv} \]  

(2)

Integral solution of (2) is the voltage $v_{pv}$ across capacitance $C_{pv}$, which is used by the PV model to calculate the PV source current. The inverter current had drawn by inverters I and II. Further, dual-inverter has two series connected equal value capacitors across the DC-link. These capacitors share equal voltage with respect to the common point ‘o’ as shown in figure 1.

**Modular three-level dual-inverter model**

To model dual inverter, switching function $S_w$ requires the logic generated from PWM controller. It has value 1 and -1 which represents turn ON of top and bottom switch respectively for the given leg or phase of the inverter. The modular dual-inverter shown in figure 1 consists of six poles ($a, b, c, a', b', c'$) and twelve switches is turned ON. If top switch of phase ‘a’, $S_1$ is turned ON, the pole voltage $v_{ao}$ is $+V_{pv}/2$ and when bottom switch of phase ‘a’, $S_4$ is turned ON then the pole voltage $v_{ao}$ is $-V_{pv}/2$.

Thus, pole voltage of inverter-I can be given as

\[ V_{ao} = \frac{V_{pv}}{2} \quad V_{bo} = S_{bb'} \frac{V_{pv}}{2} \quad V_{co} = S_{cc'} \frac{V_{pv}}{2} \]  

(3)

Similarly, pole voltage of inverter-II can be given as

\[ V_{a'o} = S_{A'} \frac{V_{pv}}{2} \quad V_{b'o} = S_{B'} \frac{V_{pv}}{2} \quad V_{c'o} = S_{C'} \frac{V_{pv}}{2} \]  

(4)

The motor phase voltage $V_{as}$ is given by

\[ V_{as} = \frac{V_{pv}}{2} \left[ \frac{1}{2} (S_{a} - S_{A'}) \right] \]  

(5)

Similarly, the other phase voltages $V_{bs}$, $V_{cs}$ of the inverter output can be derived for the system. Further, the input inverter current $i_{inv}$ can also be derived using switching functions.

Current flowing through Inverter I is given by,

\[ i_{inv} = \frac{1}{2} (S_{a} + 1) \quad i_{ao} + \frac{1}{2} (S_{n} + 1) \quad i_{bo} + \frac{1}{2} (S_{c} + 1) \quad i_{co} \]  

(6)

Current flowing through the Inverter II is given by

\[ i_{inv} = \frac{1}{2} (S_{a} + 1) (i_{ao}) + \frac{1}{2} (S_{n} + 1) (i_{bo}) + \frac{1}{2} (S_{c} + 1) (i_{co}) \]  

(7)

The net current flowing through the dual inverter is

\[ i_{inv} = \frac{1}{2} (S_{a} - S_{A'}) i_{ao} + \frac{1}{2} (S_{n} - S_{B'}) i_{bo} + \frac{1}{2} (S_{c} - S_{C'}) i_{co} \]  

(8)

Thus, the previous values of phase voltage and current can be used by the Simulink model of OEWIM, which is discussed in the next section.

**OEWIM Model**

For modeling and analysis, the decoupled form of OEWIM is considered. For transforming the stator $(p=\theta)$ and the rotor parameters $(p=\beta)$ to decoupled form, the transformation matrix used is given as follows:

\[
\begin{align*}
\begin{bmatrix}
    q \\
r
\end{bmatrix}
&= \begin{bmatrix}
    \cos \theta & \sin \theta \\
    -\sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
    r \\
r
\end{bmatrix} \\
\begin{bmatrix}
    x \\
y
\end{bmatrix}
&= \begin{bmatrix}
    \sin \frac{\theta}{2} & \cos \frac{\theta}{2} \\
    -\cos \frac{\theta}{2} & -\sin \frac{\theta}{2}
\end{bmatrix}
\begin{bmatrix}
    x' \\
y'
\end{bmatrix} \\
\begin{bmatrix}
    x \\
y
\end{bmatrix}
&= \begin{bmatrix}
    \frac{1}{2} & -\frac{1}{2} \\
    \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\begin{bmatrix}
    x' \\
y'
\end{bmatrix}
\end{align*}
\]  

(9)

where, $\theta$ is the angle between the stator as-axis and the quadrature (q) axis, $\beta$ is the angle between rotor ar-axis and the q-axis, also $\beta$=0-0,0, the angle between rotor ar-axis and stator as-axis , parameter x can be either voltage ‘v’ or current ‘i’ or flux linkage ‘$\lambda$’ and subscript parameter y can be’s’or’r’. The
subscript ‘s’ denotes the parameters of stator and the subscript ‘r’ denotes the parameters of rotor. The dynamic d-q model of an OEWIM is described by in (10) to (13).

\[ v_{qs} = R_s i_{qs} + \omega_s (L_m i_{qs} + L_s (i_{ds} + j i_{qs})) + p\lambda_{qs} \]  

(10)

\[ v_{ds} = R_s i_{ds} + \omega_s (L_m i_{ds} + L_s (i_{qs} + j i_{ds})) + p\lambda_{ds} \]  

(11)

\[ v_{qs} = R_q i_{qs} + (\alpha - \omega_s) (L_m i_{ds} + j i_{qs}) + p\lambda_{qs} \]  

(12)

\[ v_{ds} = R_q i_{ds} - (\alpha - \omega_s) (L_m i_{qs} + j i_{ds}) + p\lambda_{ds} \]  

(13)

where, \( R_s \) rotor resistance, \( R_q \) stator resistance, \( L_{ds} \) stator leakage inductance, \( L_{dr} \) rotor leakage inductance, \( L_m \) mutual inductance between stator and rotor winding, \( \omega \) is the synchronous speed, \( \omega_s \) is the electrical speed of motor, \( p \) denotes the time derivative. Also, here \( V'_{ds} = V'_{qs} = 0 \), since rotor bars are short-circuited. The expression for the electromagnetic torque \( T_{em} \) is given by,

\[ T_{em} = \frac{3}{2} P \frac{L_m}{2} [ i_{qs} \dot{\omega} - j i_{ds} \dot{\omega} ] \]  

(14)

where, \( P \) is the number of poles. The mechanical equation governing the OEWIM pump drive is expressed in (15) as,

\[ T_{mech} = J \frac{d\omega_{mech}}{dt} + B \omega_{mech}^2 + T_L \]  

(15)

where, \( J \) – motor inertia (kg-m²), \( B \) – centrifugal load torque coefficient, \( T_L \) – load torque (N-m), \( \omega_{mech} \) is instantaneous angular velocity of motor shaft (rad/sec).

Operation and analysis of the proposed system

The proposed dual-inverter is operated by using the decoupled PWM strategy. It incorporates simple \( V/f \) control for the efficient operation of system below the rated speed. The magnitude is calculated and controlled by the MPPT algorithm and the angle ‘\( \alpha \)’ is the function of time and fundamental frequency of reference modulating waveform. The reference voltage vector |\( v_{Sl} \rangle_{\alpha} \) is further divided into two decoupled components |\( v_{Sl}/2\alpha \rangle \) and |\( v_{Sl}/2\alpha(180+\alpha) \rangle \). The decoupled components are then given as the reference vector for inverter-I and inverter-II respectively as shown in figure 1, for generation of required output voltage. Thus, using decoupled PWM configuration has the benefit of double output voltage.

Low input DC bus voltage requirement of dual-inverter for OEWIM-pump drive

To analytically verify the low input DC bus voltage requirement, a comparison between two-level and dual inverter fed OEWIM is done. Both the inverters are compared for generating same output voltage vector with different values of input PV source voltage. Let the PV source voltage required to generate the rated instantaneous induction motor phase voltage, \( V_{an} \) is \( V_{pv} \) as shown in figure 2(a). From figure 2(a) and 2(b) the inverter output voltage, \( V_{an}, V_{bn} \) and \( V_{cn} \) can be obtained using the inverter pole voltage, \( V_{ao}, V_{bo} \) and \( V_{co} \); and switching functions \( S_A, S_B \) and \( S_C \) as follows:

\[ V_{an} = V_{ao} - V_{bo} = (\frac{2}{3} S_A - \frac{1}{3} S_B + S_C) \frac{V_{pv}}{2} \]  

(16)

Where \( V_{ao} \) is common-mode voltage given by,

\[ V_{ao} = \frac{1}{3} (V_{ao} + V_{bo} + V_{co}) = \frac{1}{3} (S_A + S_B + S_C) \frac{V_{pv}}{2} \]  

(17)

Fig. 2. Demonstration and comparison of DC bus voltage requirement for H bridge and dual-inverter systems.

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(a) Schematic circuit diagram of two-level H-bridge inverter with input DC voltage (PV voltage) of ‘V_{dp}’;
(b) Space vector locations of voltage vector obtained from two-level inverter; (c) Schematic circuit diagram of dual-inverter fed OEWIM drive with input DC voltage (PV voltage) of ‘V_{dp}/2’; (d) Space vector locations of voltage vector obtained from three-level dual-inverter scheme.

Thus, the space vector location of reference voltage vector OA (Fig. 2b) can be generated by the switching functions \( S_a=1, S_b=-1 \) and \( S_c=1 \).

Substituting these values in (17) will result in the phase voltage, \( v_{oa} \) as \( 2 V_{dp}/3 \). Now, consider the 3-phase, three-level dual-inverter connected to an OEWIM as shown in figure 2(c). Let the input PV source voltage is \( V_{dp}/2 \), which is half of the voltage taken for two-level H-bridge inverter. Now, the dual-inverter output phase voltage OG (Fig. 2(d)) is given as:

\[
V_{oa} = V_{ov} - V_{oa'} - V_{oo'}
\]

Where \( V_{oo'} \) is the common mode voltage (Fig. 2(c)) which is given by,

\[
V_{oo'} = \frac{V_{dp}}{4} (S_a - S_A) + (S_b - S_B) + (S_c - S_C)
\]

(19)

Therefore, \( v_{oa} \) is given by,

\[
V_{oa} = \frac{(S_a - S_A)}{3} - \frac{(S_b - S_B)}{3} + (S_c - S_C) \frac{V_{dp}}{4}
\]

(20)

So, to generate voltage vector OG [see Fig. 2(d)], the switching functions required are \( S_A=1 \), \( S_B=-1 \), and \( S_C=1 \). Substituting these values in (20), results in the phase voltage of magnitude \( 2 V_{dp}/3 \) corresponding to phase \( aa' \).

Hence, to generate the phase voltage of \( 2 V_{dp}/3 \), the PV source voltage required in case of two-level inverter is \( V_{dp} \) and incase of dual inverter connected to OEWIM is \( V_{dp}/2 \). However, the DSAZE PWM technique needs excess 15% of DC-link voltage to generate the rated motor phase voltage.

Control strategy and mppt algorithm

The solar PV-powered-fed dual inverter connected to OEWIM-pump drive is operated using a simple control strategy which simultaneously accomplishes MPPT and DSAZE PWM integrated together. This integrated algorithm generates the required PWM control signals for the modular dual inverter. The MPPT part of algorithm facilitates motor-pump drive to extract maximum available power from the PV source, thereby assuring effective utilization of the PV source. The DSAZEPWM part of the algorithm incorporates \( V/f \) control. It maintains constant rated flux in the motor which retains the maximum torque capability of the machine for the given PV power.

MPPT Algorithm

One of the simplest, most popular, and commercially used methods of MPPT, namely, the Ripple Correlation Control is employed in the proposed system. The algorithm first senses the voltage (\( v_{p} \)) and current (\( i_{p} \)) of PV array for calculating the power (\( p_{p} \)). The considered slope then determines the correction for modulation index (\( m_{a} \)). With respect to sign of the slope (negative or positive), the value of \( m_{a} \) is modified (incremented or decremented) until the operating point reaches near MPP. The calculated value of \( m_{a} \) is then used by the DSAZE PWM algorithm.

DSAZE PWM Algorithm

The magnitude of the reference voltage vector generated by the MPPT output and angle ‘\( \alpha \)’ is
decomposed into the instantaneous three-phase reference voltage $v_{sa}$, $v_{sb}$, and $v_{sc}$ for Inverter I. The gating time $T_{gj}(j = a, b, c)$ for top switches of Inverter I (Fig. 2) is then obtained by the switching algorithm. This algorithm requires instantaneous values of the reference phase voltage for calculating the effective time (time for which all the active vectors are switched) or turned ON time for top switches. The position of effective time period can be adjusted in such a way that the offset time is equal to $T_s/2$ within a switching period. As DSAZE is a center-spaced PWM technique for the dual inverter system, the ripple content in current is less and hence results in the improvement of developed torque. The other advantage of the DSAZE PWM algorithm for OEWIM drive that it requires less memory and computing time for processing is less. As both the reference voltage vectors for Inverters I and II are in the phase opposition, the gating time $T_{g_{llj}}(j = a, b, c)$ for the top switches of Inverter II are directly obtained using the gating time for Inverter I as follows:

$$T_{g_{llj}} = T_s - T_{gj}$$  (21)

Where $j = a, b, c$ and $T_s$ is the inverter switching time period(s). Complement of the respective gating signals for Inverters I and II are generated for bottom switches for both inverters.

**MPPT Ripple correlation control**

Ripple correlation control (RCC) was first proposed by Midya et al. (1996) for MPPT and motor efficiency optimization purposes. Inexpensive and robust controllers utilizing an analog RCC technique have also been developed by Esram et al. (2007), Il-Song and Myung-Joong (2004) and Lim and Hamill (2000, 2001). RCC makes use of converter ripple as an alternate source of perturbation. The maximum power point is usually located by correlating the derivative of the array power with the voltage or current ripple waveform. As, Midya et al. (1996:1710) noted, a major benefit of RCC is that it ‘keeps [DC–DC] converter operation at the optimum point’ while avoiding the ‘inconvenient, slow, and fundamentally sub-optimal’ perturbation process described in previous sections. The concept of distributed generation has enabled any individual single-phase consumer to generate power and also sell the excess power to the utility grid. Because of this, small single phase photovoltaic (PV) generating units are becoming more and more popular. Such distributed units should be operated reliably without much maintenance and should be cost effective. A typical single phase grid connected PV system has more than one stage of energy conversion. The first stage is usually a DC-DC converter, which boosts the dc-link voltage level such that it can draw peak available power from PV panels. The second stage is an inverter, which ensures that whatever the energy extracted from PV array is fed to the utility grid. The cost and complexity of the system can be reduced by employing a single-stage topology. Moreover, such a system can be more reliable, because of the reduced component count. The schematic of a typical single-stage PV system in which the output of PV array is fed to the utility grid. The DC-AC inverter present in single stage systems performs the function of extracting the peak available power as well as dumping the extracted power to the grid.
As the average value of error signal indicates the distance of the operating point from MPP, the operating point can be controlled by passing the average error signal through a PI controller. Hence, the implementation of the proposed MPPT algorithm (Satish et al., 2015). The ripples \( \hat{V}(t) \) and \( \hat{P}(t) \) can be obtained by subtracting the average values from the respective signals using LPFs. The product of these ripples is used as input to a PI controller. The output of the PI controller is considered as reference signal, \( V^*(t) \) to control the DC-link voltage. The reference signal thus obtained is compared with PV array voltage and the error obtained is passed through another PI controller to obtain the load angle \( \hat{\theta} \). This angle is used to generate the control signals to operate the inverter switches.

Simulation results

The single-stage Photo voltaic-powered OEWIM drive for pump application, shown in figure 1, is simulated using MATLAB/Simulink. A 3.6 kW (20×3) PV array feeding power to a 4 kW OEWIM-pump drive is considered for simulation. The SolarexMSX60 PV panel parameters under standard test conditions are \( V_{oc} = 21V, \ I_{sc} = 3.74A, \ V_{m} = 17.1V, \ I_{m} = 3.5A, \) and \( P_{m} = 59.9W \). A DC-bus capacitor (Cpv) of value 1000 \( \mu F \) is used at the output of PV source. A four-pole, 400 V, 1430 r/min Induction Motor is used. Further the important parameters of the motor are \( R_s=1.405W, \ R_r=1.395W, \ x_{ds}= x_{dl} = 1.8344W, \) and \( x_{m} = 54.0982W \). Simulations are performed by considering 96 samples per cycle of applied fundamental voltage, irrespective of the modulation index. This means that the switching frequency is a variable quantity. The switching frequency varies from 1.28 kHz (corresponding to a modulation index, \( m_a=0.2 \) with fundamental frequency \( f = 13.33 \text{ Hz} \)) to 4.8 kHz (corresponding to a modulation index, \( m_a \geq 0.75 \) with fundamental frequency \( f = 50 \text{ Hz} \)). Thus, slip power loss increases and decreases with increase and decrease of PV power, respectively.

Fig. 3. Simulation results showing waveforms at PV source side

Figure 3 shows the simulation results of the proposed system under different environmental conditions for PV source-side parameters. The increasing and decreasing nature of PV power with respect to insolation \( (G) \) and temperature \( (T) \) can be observed with the waveforms of PV power and \( m_a \). This verifies the MPP tracking, further small
oscillations in the value of $m_a$ near MPP and small ripple content in a PV power confirms the operation near optimum voltage.

**Fig. 4.** Simulation results showing waveforms at motor-pump side.

Also, another useful observation in the simulation results is that the operating voltage of PV array passes through optimum voltage for every step increase in insolation and temperature. This can be justified with the matching values of peak power value during transient tracking and steady state near MPP as given in the PV power subplot. Further, it can be noted that PV voltage waveform shows a sudden rise and fall in the value with the step increase in insolation and temperature. This can be attributed to charging and discharging of PV capacitor $C_{PV}$ with excess or deficit PV power, respectively, during transient condition.

**Fig. 5.** Harmonic spectrum of motor phase current ($i_{ma}$) at steady state obtained from simulation at different environmental conditions; (a) at 0.1 insolation and 25°C; (b) at 0.6 insolation and 35°C; (c) at 1.0 insolation and 55°C. (a)
Figure 4 shows the motor-side parameters for different environmental conditions. Variation on $m_a$ with respect to PV power can also be seen here in the waveform of torque, speed, and mechanical power output. It can be observed that torque, speed, and mechanical power output follow $m_a$ or the PV power indirectly. Another typical difference between figures 4 and 5 is the ripple contents in the motor phase current and torque waveform follows $m_a$. Also, it can be easily observed that slip power too follows $m_a$. This may help in keeping small variation in efficiency which can be observed from last subplot of Fig. 9. Also, another important feature that relate results of Figs.3 and 4 is motor phase voltage plot. The transient variations in PV voltage $V_{pv}$ during step increase in insolation can be depicted with a peak value of motor phase voltage waveform.

**Conclusion**

An integrated single-stage solution of PV-fed pump drive is presented by MPPT correlation control method. The proposed system has the feature of low dc-bus voltage requirement, MPPT integrated with V/f, three-level inverter operation and low cost. Analytical proof for low DC-bus voltage requirement in the proposed system is presented. Implementation of V/f with MPPT can be verified with simulation results. A high-performance integrated solution is proposed. Low cost of proposed system can be attributed to requirement of low voltage DC-link bus capacitor, low voltage rating switches, and less number of sensors for integrated control operation. The concept presents one of the effective and simple solutions for PV power-fed water-pump application.

**References**


