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Design and Implementation of a Dynamic Evolution Controller for Single-phase Inverters with Large Load Changes

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CONTENTS

Abstract—A new controller is developed for a single-phase inverter based on the dynamic evolution control method. The non-linear model equations and algorithm of the approach is derived and presented. The simulation is conducted based on the proposed method by MATLAB/Simulink to test the performance of the controller for large load variations. The system was also tested experimentally to show the feasibility of the proposed method applied to a single-phase inverter. Results show that the proposed approach is suitable for applications with large load variations. Practical results show that the controller can successfully handle a 40 times load change in less than 2 ms. It also has good output in the harmonic spectrum compared with the IEEE 519 harmonic standard during no-load and full-load conditions.

1. INTRODUCTION

Inverters are the most important components for many power conversion applications, such as the uninterruptible power supply (UPS), power quality devices, such as a unified power quality conditioner [1], motor control drives, induction heating, and renewable energy systems [2–5]. The main feature of a well-designed inverter is its ability to provide high-quality and stable AC voltage regardless of the output load. One of the major challenges ahead of the converters is the load change. New electric devices need different power levels at different times, and the inverter should have the ability to recover as quickly as possible from transient conditions caused by load changes [6].

In recent years, various instantaneous feedback control methods on a linear model have been proposed [6–9]. Normally when designing controllers using the conventional linear model control theory, such as proportional integrator (PI) and proportional integral derivative (PID) controllers, small-signal linear approximations are applied to the non-linear system. This approach enables the designer to implement a simple linear controller to a system. However, the main disadvantage of

Keywords: dynamic evolution control, single-phase inverter, inverter control, load change, power quality, power electronics, harmonic
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PI and PID controllers is that they need the precise mathematical model of the system and can only work close to a specified operating point. Therefore, the controller parameters are not feasible for dynamic operating points that require large parameter changes. This restricts their applications and is difficult to implement for large changes in loads conditions, such as data centers and telecommunication equipment [10].

For the past few decades, many control techniques have been proposed for power inverter applications. Since power inverters are non-linear time-varying systems, the design of suitable controllers requires consideration of the non-linearity and time-varying properties of the inverter system. An inverter deals with many uncertainties and variations, such as system parameter variations, non-linearity, load disturbance, etc. Therefore, conventional linear methods (such as PI controllers) are not suitable for this purpose, especially in extreme load changes. Moreover, these controllers usually need a pulse width modulation (PWM) controller to drive the semiconductor switches, which adds to the complexities of the approaches [11].

A well-known method to control inverters is the dq method. This approach transforms variable AC line values to fixed quantities. However, this method is basically introduced for three-phase systems and needs modifications for single-phase applications. To adapt this method for single-phase systems, measured voltage and current should be shifted by a quarter-line cycle; this needs exact frequency calculations, especially during load changes. This shows that this method is quite complex especially for implantation purposes. To avoid problems with this method during load changes, the concept of fictive axis emulation is introduced, adding to the complexity of the approach [12]. To overcome the restrictions of linear control methods for inverter control, researchers have proposed several non-linear control methods. The fuzzy control method a well-known method to overcome linear method shortcomings [8, 9]. Although it is more robust and does not need a system mathematical model, it is highly based on experience, and its rules and structure are mostly designed by trial and error [10]. It also needs extensive and complex calculations to determine the suitable output.

Another non-linear control method used for inverter application is predictive model control. However, this method requires an observer to improve the inverter performance, which adds to the complexities of the method. To tune the observer speed, accurate pole placement should be done, and this requires additional knowledge about system performance [13].

In this article, a new approach for an inverter controller based on the dynamic evolution control (DEC) theory [14–17] is proposed and implemented. DEC exploits the non-linearity and time-varying properties of the system to make it a superior controller. DEC is superior over conventional control methods in terms of steady-state error, stability, and robustness.

Implementation of the method is quite simple and does not need complex calculations; therefore, it is suitable for digital applications and digital signal processor (DSP) implementation. It operates in constant switching frequency and, hence, does not cause interference and filtering problems as in such variable switching frequency methods as the hysteresis method. Although this method is implemented on DC-DC converters, it has not been tested on inverter applications that need an alternative reference.

Sliding-mode control seems to be suitable for inverter control applications [18–20]. However, its coefficients need to be updated continuously to improve its tracking capability. Therefore, it needs extensive calculations [21] or some form of intelligent control or fuzzy logic to determine the continuously changing coefficients. It also suffers from a chattering problem that leads to variable and high-frequency switching in the converter [22].

In comparison with other new control methods, the proposed method has better results in terms of power quality and a simpler structure for implementation; therefore, it does not need fast and high-speed processors, such as field programmable gate array (FPGA). FPGA-based controllers suffer from a long prototyping development time and troubleshooting complexities. When good control performance is required, coding must be done in hardware description language (HDL), leading to substantial efforts during the design of the hardware architecture [23]. In [24], multi-dimensional calculations were carried out by FPGA, which made it more complex compared to conventional space vector modulation (SVM) control [12, 25]. This method also generates sideband harmonics that can interfere in control loops and are difficult to remove by filters [26]. It therefore needs higher-order shaping filters that add to the complexities of the approach [24].

The proposed approach also does not need to calculate the pole and zeros of the system to enhance the performance of the controller [27]. This method has also wide range of stability as experimentally proven and does not suffer from system parameter change instability [28].

2. DEC

2.1. Principle of DEC

Feedback control methods are used when a disturbance or change is applied during normal circuit operation. These methods reduce the difference between the reference and actual operating point [29].

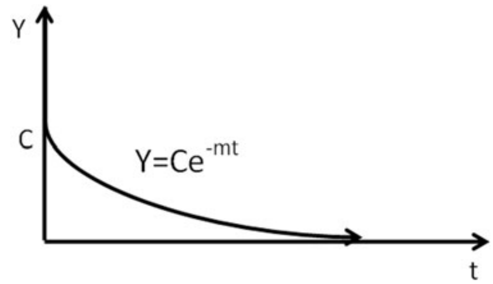

FIGURE 1. Dynamic evolution path.

The principle of DEC is also based on reduction of the difference (error) between reference and actual operating points. This difference is that the error state is forced to zero by following a specified path; therefore, the error state rapidly decreases to zero after a disturbance.

2.2. Evolution Path and DEC

The main objective of the DEC method is to control the dynamic characteristic of the system so that the state error (Y) becomes zero ($Y = 0$); therefore, an evolution path for state error is adopted to make it zero after several cycles.

The following exponential function is selected for the evolution path of the state error in this research due to its fast response and simple structure:

$$Y = Ce^{-mt}, \tag{1}$$

where C is the initial value of error state (Y), and m is a coefficient for the decrease rate of the error state. As m becomes larger, the error decreases faster according to the exponential function expression.

The evolution path is shown in Figure 1. In this exponential function, the value of Y is reduced exponentially to zero as a function of time. The reduction speed of the state error (Y) is proportional to m. C is the initial value of state error (Y_0), and the following equation is obtained:

$$Y = Y_0 e^{-mt}. \tag{2}$$

The derivative of Y is found as follows:

$$\frac{dY}{dt} = -mY_0 e^{-mt}. \tag{3}$$

This equation can be written as follows:

$$\frac{dY}{dt} = -mY. \tag{4}$$

Therefore, the state error equation for dynamic evolution is obtained as

$$\frac{dY}{dt} + mY = 0. \tag{5}$$

In this equation, m is a positive integer specifying the decrease rate of the state error in DEC.

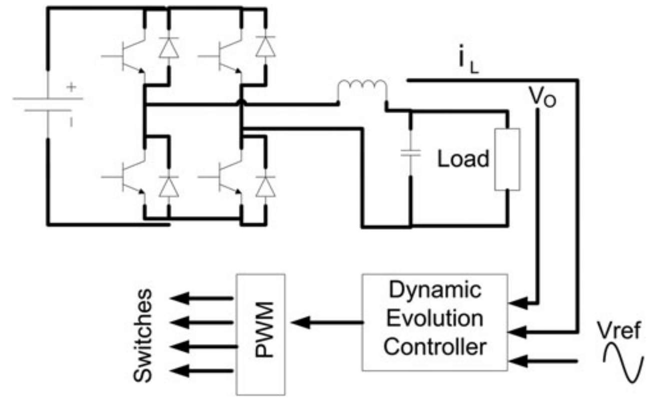

FIGURE 2. Inverter general schematic diagram.

2.3. Application of DEC on Single-phase Inverter

To apply the proposed control method on an inverter, the state error equation based on inverter parameters should be obtained. Therefore, the controller determines the appropriate value for the duty cycle to follow the evolution path and decrease the state error to zero.

The general schematic diagram of a single-phase inverter is depicted in Figure 2. Operation of the circuit is mainly divided into two states: positive and negative. In the positive state, the output voltage has positive polarity, and the inverter switches between zero and DC voltage (V_{DC}). On the other hand, the output voltage polarity toggles between $-V_{DC}$ and zero to generate negative polarity in the negative state.

In the positive state, the circuit operation is also divided into two cases. In the first case, S1 and S2 are on while other switches are off and DC voltage is applied to the output load. The circuit characteristic equation is as follows:

$$V_{dc} = L\frac{di_L}{dt} + V_0. \tag{6}$$

In the second case, S1 and S2 are off to apply zero voltage to the output load. The circuit characteristic equation is as follows:

$$0 = L\frac{di_L}{dt} + V_0. \tag{7}$$

To average the circuit characteristics over a complete switching period, volt-second equations are obtained from the circuit characteristic equations. Therefore, the duration of each case is multiplied by the characteristic equation. The volt-second equation for the first case is found by multiplying Eq. (6) by the on time (t_{on}) as follows:

$$V_{dc}.t_{on} = \left(L\frac{di_L}{dt} + V_0\right).t_{on}. \tag{8}$$

In the second case, Eq. (7) is multiplied by the off time (t_{off}) as follows:

$$0 = \left(L\frac{di_L}{dt} + V_0 \right).t_{off}. \tag{9}$$

To find the overall equation in this state, Eqs. (9) and (8) are added together as follows:

$$V_{dc}.t_{on} = \left(L\frac{di_L}{dt} + V_0 \right).t_{on} + \left(L\frac{di_L}{dt} + V_0 \right).t_{off}. \tag{10}$$

In a switching period, the off time (t_{off}) and on time (t_{on}) generate the overall switching period (T) and can therefore be replaced as follows:

$$T_{off} = T - T_{on}. \tag{11}$$

Duty cycle (α) is also relevant to on time (t_{on}) as follows:

$$\propto = \frac{t_{on}}{T}. \tag{12}$$

Replacing Eq. (11) into Eq. (10) and dividing the whole equation by the switching period (T), the final characteristic equation for state 1 is obtained:

$$V_0 = \propto .V_{DC} - L\frac{di_L}{dt}. \tag{13}$$

The same procedure can be followed to determine the characteristic equation for state 2. The final characteristic equation for state 2 is as follows:

$$V_0 = -\propto .V_{DC} - L\frac{di_L}{dt}. \tag{14}$$

To apply DEC on the inverter as in Eq. (1), the state error function is defined as follows:

$$Y = kV_{err}, \tag{15}$$

where k is a positive coefficient and is considered a small fractional number (such as 0.01). V_{err} is defined as voltage error as follows:

$$V_{err} = V_{ref} - V_0. \tag{16}$$

The derivative of Y is found as follows:

$$\frac{dY}{dt} = k\frac{dV_{err}}{dt}. \tag{17}$$

Replacing Eqs. (17) and (15) into Eq. (5) gives

$$k\frac{dV_{err}}{dt} + m.k.V_{err} = 0. \tag{18}$$

Equation (18) can be rearranged as follows:

$$k\frac{dV_{err}}{dt} + m.k.V_{err} = V_{err} - V_{err}; \tag{19}$$

this leads to

$$k\frac{dV_{err}}{dt} + (m.k - 1).V_{err} = -V_{err}. \tag{20}$$

Substituting Eq. (16) into Eq. (20) yields

$$k\frac{dV_{err}}{dt} + (m.k - 1).V_{err} = V_0 - V_{ref}. \tag{21}$$

To find the duty cycle, V_0 should be replaced in Eq. (21) based on available states. In state 1, Eq. (13) is used in Eq. (21) to find the duty cycle as follows:

$$k\frac{dV_{err}}{dt} + (m.k - 1).V_{err} = \left(\propto .V_{DC} - L\frac{di_L}{dt} \right) - V_{ref}. \tag{22}$$

Therefore, the duty cycle is obtained from Eq. (22) as follows for state 1:

$$\propto = \left(k\frac{dV_{err}}{dt} + (m.k - 1).V_{err} + V_{ref} + L\frac{di_L}{dt} \right) \Big/ V_{DC}. \tag{23}$$

The same procedure is true for state 2, which leads to

$$\propto = -\left(k\frac{dV_{err}}{dt} + (m.k - 1).V_{err} + V_{ref} + L\frac{di_L}{dt} \right) \Big/ V_{DC}. \tag{24}$$

Equations (23) and (24) are used to calculate the appropriate duty cycle for the inverter. Therefore, output voltage deviation from the reference in inverter (error state) will follow the evolution path to reduce the error state to zero and reach its target reference. k is a scaling factor to downscale the actual values used in the calculations, and in this work, k is set at 0.1. m functions as the error convergence, and if it is set high, the errors converge rapidly, thus having good response to load changes. However, if it is set too high, overshoots in the error may occur due to the overflow in the DSP registers. In this work, m is iteratively selected to ensure good response without overshooting the error.

In comparison with [30], this controller presents better results in terms of the harmonic spectrum due to its output switching levels. The proposed controller switches between V_{DC} and zero in the positive cycle and $-V_{DC}$ and zero in the negative cycle (the output voltage change is equal to V_{DC} in both cycles), while the controller in [30] switches between $-V_{DC}$ and V_{DC} (equal to $2.V_{DC}$), which is double the amount of change in the proposed controller. Therefore, the voltage stress in the output load for the proposed method is half that of [30]. This will also decrease the sensitivity of the output voltage to duty cycle in the proposed controller. It means that with a change in duty cycle, in the proposed method, the output change is smaller compared to [30] due to the smaller output voltage changes. This will improve the quality of the output voltage.

DEC theoretically does not need the exact knowledge of the model parameters. It only needs the value of the output filter inductance (L).

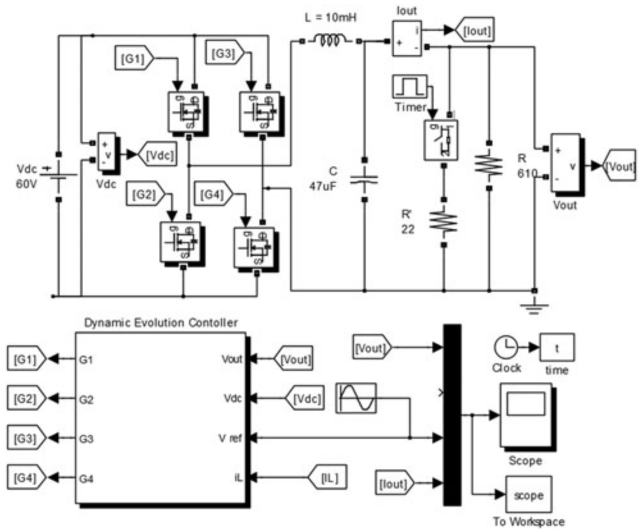

FIGURE 3. General block diagram for simulation.

This requirement creates a small limitation on the control system since it is sometimes difficult to obtain the exact value of L. In practice, small changes in inductor value do not affect the overall controller performance.

3. SIMULATION RESULTS

Simulation is done by MATLAB/Simulink (The MathWorks, Natick, Massachusetts, USA) to verify the controller performance. Figure 3 shows the simulation model. In this model, a single-phase inverter is controlled by the proposed method.

The most important capability of DEC is its ability to respond effectively under a step load change condition. Therefore, a load change is imposed to the inverter to investigate its dynamic performance.

Circuit parameters for simulation are also mentioned in Table 1. The output load RMS current is 28 mA in steady state; it then suddenly changes to 1.28 A, which is a large load change, to show the capability of controller to overcome large load conditions.

Circuit parameter	Value
Input DC voltage	60 V
Peak output voltage	40 V
No load resistance	1 Kohm
Load change resistance	22 ohm
Switching frequency	20 kHz
Line frequency	50 Hz
Output inductor	10 mH
Output capacitor	47 μF
k	0.01
m	2000

TABLE 1. Circuit parameters for simulation

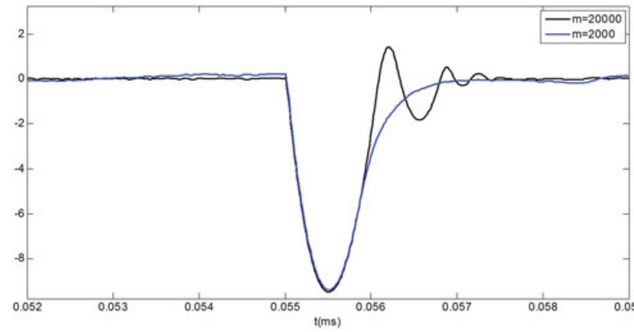

FIGURE 4. Error during load change for different m ($m = 2000$, $m = 20{,}000$).

To show the effect of m on the results, the error voltage (V_{err}) is depicted in Figure 4 during load change for different values of m. As m increases from 2000 to 20,000, oscillation and overshoot occur in the error.

The inverter output voltage and current together with the reference voltage are shown in Figure 5. As shown in Figure 5, initially, the inverter operates in almost no load. A large load change occurs at $t = 55$ ms. The inverter output voltage follows the reference in all instances. However, there is a small output voltage drop during the load change that lasts less than 2 ms. This voltage drop is approximately 25% and is small compared to the large amount of load change. The proposed controller is able to respond fast and is stable enough to handle large load changes.

The next section presents the experimental results for the controller to illustrate the practical capability of the controller. A prototype is built based on the simulation results and with the same circuit parameters.

4. EXPERIMENTAL RESULTS

A single-phase inverter prototype is built based on the simulation results. This prototype is controlled by a dSPACE (ds1104)

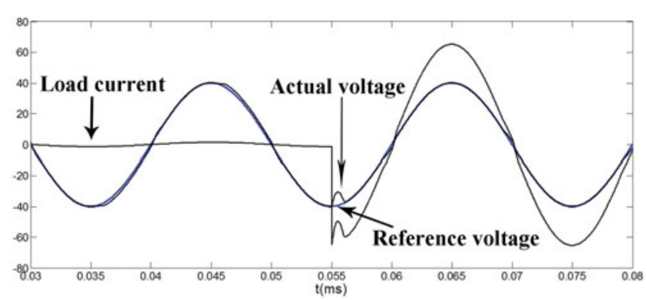

FIGURE 5. Simulation results for proposed method.

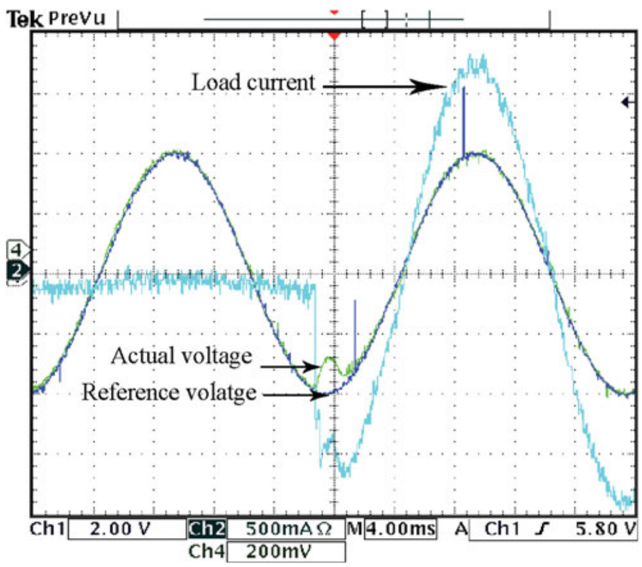

FIGURE 6. Experimental results of the proposed controller during no-load to full-load change, inverter output current (0.5 A/div), inverter output voltage (20 V/div), and inverter reference voltage (20 V/div).

DSP (dSPACE GmbH, Paderborn, Germany) that is compatible with MATLAB.

The control method is developed and simulated in a MATLAB/Simulink environment. The same blocks used in this environment are adopted for the DSP. Then it is compiled and downloaded into the DSP to control the inverter. The DSP receives the value of inverter voltage and current and generates the appropriate duty cycle according to the developed dynamic evaluation control. An isolated voltage transducer (LV25-P, LEM Company, Kuala Lumpur, Malaysia) is used as a voltage sensor in this experiment, and the current is measured through a Hall effect ACS712 sensor (Allegro Microsystems Company, Penang, Malaysia).

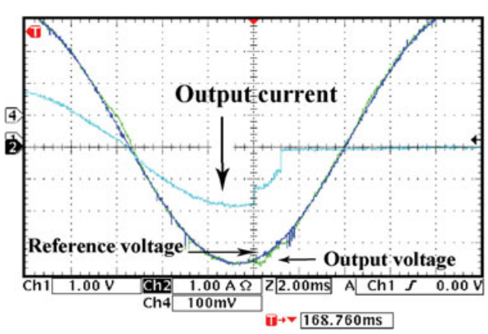

FIGURE 7. Dynamic results of the proposed controller during full-load to no-load change, reference voltage, output voltage and current, inverter output current (1 A/div), inverter output voltage (20 V/div), and inverter reference voltage (20 V/div).

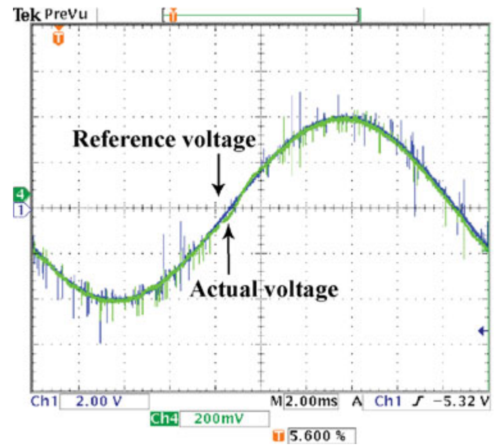

FIGURE 8. Experimental results for static performance of proposed controller during full load, actual voltage, and reference voltage (10 V/div).

The experimental circuit parameters are the same as in Table 1. The almost no-load power was only 0.9 W, measured using a power analyzer. To investigate the dynamic performance of the proposed controller, a large load change is imposed on the inverter. In the experiment, the load is changed from 0.9 to 36.1 W, which is about 40 times larger.

Figure 6 experimentally demonstrates the dynamic performance of the controller during load changes. The controller can successfully respond to large changes in the output voltage and follow the reference rapidly. It illustrates that this major load change generates approximately a 30% voltage drop and lasts less than 2 ms. The capability of the controller to overcome large signal disturbances without instability problems is also shown in this figure.

Figure 7 shows the capability of the controller for a step-down load. The voltage is controlled according to the reference value with only a little disturbance. Unlike the approach in [31], the proposed approach does not have overshoot during a full-load to no-load change. The load current does not drop sharply to a no-load current due to the effect of the filter inductor.

Figure 8 exhibits experimental results of inverter output voltage together with the reference that is generated by a DSP built in a digital-to-analog converter.

As discussed earlier, the controller presents good output power quality that is proven by the experimental results.

Figure 9 illustrates inverter output voltage and current during no-load conditions. The voltage total harmonic distortion (THD) was 0.88% measured using a power analyzer.

Inverter output voltage and current during full-load conditions are shown in Figure 10. Voltage THD in this case is 2.6%, which is in compliance with the IEEE 519 harmonic standard.

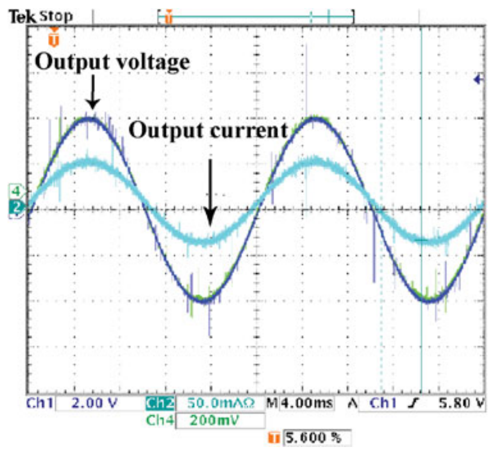

FIGURE 9. Inverter output voltage (20 V/div) and current (50 mA/div) during no-load conditions.

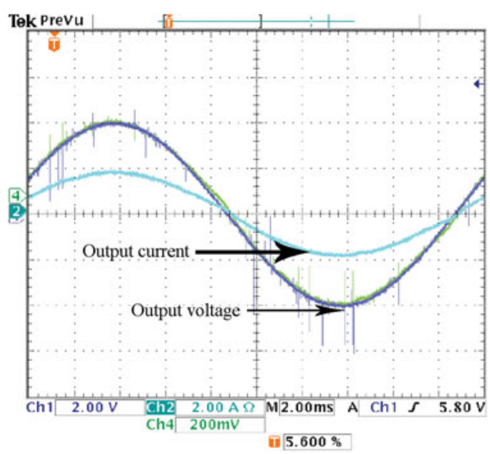

FIGURE 10. Inverter output voltage (20 V/div) and current (2 A/div) during full-load conditions.

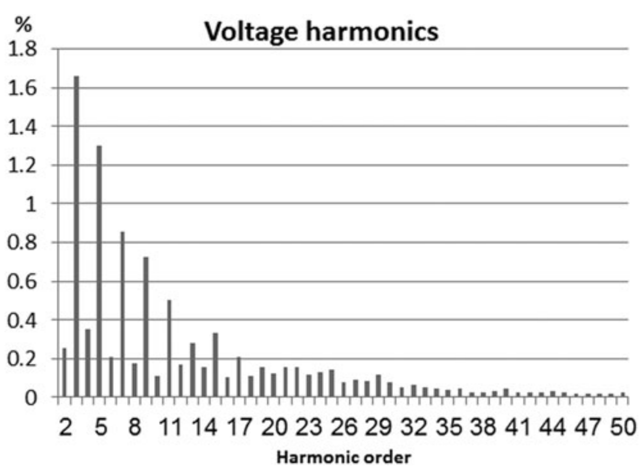

FIGURE 11. Harmonic spectrum of output voltage during full-load conditions, percentage of each harmonic order compared to fundamental harmonic order (50 Hz).

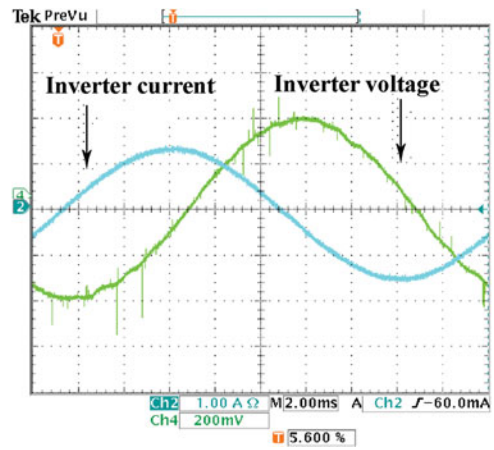

FIGURE 12. Experimental results for static performance of proposed controller with reactive load, inverter output voltage (20 V/div), and current (1 A/div).

The harmonic spectrum in this condition is also depicted in Figure 11, which verifies the good output voltage quality of the controller due to the selected output voltage levels.

Finally, the performance of the controller for a reactive load is also investigated, as shown in Figure 12. A 90-mH inductor is placed in series with a light resistive load to observe the inverter output voltage and current for reactive loads. The result in Figure 12 shows that the controller can work successfully for both resistive and inductive loads.

5. CONCLUSION

This article presents a new controller based on the DEC method for inverter applications. DEC for single-phase applications proved to be effective and fast, especially for large load changes.

A simulation is done based on the derived mathematical model for the controller. Then an experimental setup is developed to show the feasibility of the control method applied to inverters. The practical results show that the controller is capable of responding rapidly to the load change with a small dip lasting for 2 ms. The output power quality has low harmonics and is within the standard limits.

REFERENCES

[1] Pal, Y., Swarup, A., and Singh, B., "Flexible control of single-phase unified power quality conditioner using frequency-domain approach," *Elect. Power Compon. Syst.*, Vol. 41, pp. 401–412, 2013.

[2] Huang, X., Wang, Z., and Jiang, J., "Control and load-dispatching strategies for a microgrid with a DC/AC inverter of fixed frequency," *Int. J. Elect. Power Energy Syst.*, Vol. 43, pp. 1127–1136, 2012.

[3] Ramkumar, S., Kamaraj, V., Thamizharasan, S., and Jeevananthan, S., "A new series parallel switched multilevel DC-link inverter topology," *Int. J. Elect. Power Energy Syst.*, Vol. 36, pp. 93–99, 2012.

[4] Maleki, M. K. H., "Frequency control of microgrids in autonomous mode by a novel control scheme based on droop characteristics," *Elect. Power Compon. Syst.*, Vol. 41, pp. 16–30, 2013.

[5] Colak, I., and Kabalci, E., "Implementation of energy-efficient inverter for renewable energy sources," *Elect. Power Compon. Syst.*, Vol. 41, pp. 31–46, 2012.

[6] Ayob, S. M., Azli, N. A., and Salam, Z., "Single input PI-fuzzy controller for single phase inverter system," *IREE*, Vol. 3, pp. 418–425, 2008.

[7] Habetler, T. G., and Harley, R. G., "Power electronic converter and system control," *Proc. IEEE*, Vol. 89, pp. 913–925, 2001.

[8] Ying-Yu, T., and Shih-Liang, J., "Full control of a PWM DC-AC converter for AC voltage regulation," *IEEE Trans. Aerospace Electron. Syst.*, Vol. 34, pp. 1218–1226, 1998.

[9] Tsang-Li, T., and Jian-Shiang, C., "UPS inverter design using discrete-time sliding-mode control scheme," *IEEE Trans. Indust. Electron.*, Vol. 49, pp. 67–75, 2002.

[10] Raviraj, V. S. C., and Sen, P. C., "Comparative study of proportional-integral, sliding mode, and fuzzy logic controllers for power converters," *IEEE Trans. Indust. Appl.*, Vol. 33, pp. 518–524, 1997.

[11] Sotoodeh, P., and Miller, R. D., "A novel single-phase inverter with distribution static compensator capability for wind applications," *Elect. Power Compon. Syst.*, Vol. 41, pp. 1294–1310, 2013.

[12] Ninad, N. A., and Lopes, L. A. C., "A vector-controlled single-phase voltage source inverter based grid interface suitable for variable frequency operation in autonomous microgrids," *Elect. Power Compon. Syst.*, Vol. 40, pp. 1266–1284, 2012.

[13] Cortes, P., Ortiz, G., Yuz, J. I., Rodrigues, J., Vazquaz, and Franquelo, L. G., "Model predictive control of an inverter with output LC filter for UPS applications," *IEEE Trans. Indust. Electron.*, Vol. 56, pp. 1875–1883, 2009.

[14] Samosir, A. H. M. Y. A. S., "Implementation of new control method based on dynamic evolution control for DC-DC power converter," *IREE*, Vol. 4, pp. 1–6, 2009.

[15] Samosir, A. S., and Yatim, A. H. M., "Implementation of new control method based on dynamic evolution control with linear evolution path for boost DC-DC converter," *IEEE 2nd International Power and Energy Conference (PECon 2008)*, pp. 213–218, Johor Bahru, Malaysia, 1–3 December 2008.

[16] Samosir, A. S., and Yatim, A., "Dynamic evolution control of bidirectional DC-DC converter for interfacing ultracapacitor energy storage to fuel cell electric vehicle system," *Australasian Universities Power Engineering Conference (AUPEC '08)*, pp. 1–6, Australia, 14–17 December 2008.

[17] Samosir, A. S., and Yatim, A. H. M., "Implementation of dynamic evolution control of bidirectional DC-DC converter for interfacing ultracapacitor energy storage to fuel-cell system," *IEEE Trans. Indust. Electron.*, Vol. 57, pp. 3468–3473, 2010.

[18] Sofla, M. A., and Gharehpetian, G. B., "Dynamic performance enhancement of microgrids by advanced sliding mode controller," *Int. J. Elect. Power Energy Syst.*, Vol. 33, pp. 1–7, 2011.

[19] Ghamri, A., Benchouia, M. T., and Golea, A., "Sliding-mode control based three-phase shunt active power filter: Simulation and experimentation," *Elect. Power Compon. Syst.*, Vol. 40, pp. 383–398, 2012.

[20] Lin, W.-B., Chen, C.-A., and Chiang, H.-K., "Design and implementation of a sliding mode controller using a Gaussian radial basis function neural network estimator for a synchronous reluctance motor speed drive," *Elect. Power Compon. Syst.*, Vol. 39, pp. 548–562, 2011.

[21] Komurcugil, H., "Rotating-sliding-line-based sliding-mode control for single-phase UPS inverters," *IEEE Trans. Indust. Electron.*, Vol. 59, pp. 3719–3726, 2012.

[22] Jiabing, H., Lei, S., Yikang, H., and Zhu, Z. Z., "Direct active and reactive power regulation of grid-connected DC/AC converters using sliding mode control approach," *IEEE Trans. Power Electron.*, Vol. 26, pp. 210–222, 2011.

[23] Buccella, C., Cecati, C., and Latafat, H., "Digital control of power converters—a survey," *IEEE Trans. Indust. Informat.*, Vol. 8, pp. 437–447, 2012.

[24] Jwu-Sheng, H., Keng-Yuan, C., Te-Yang, S., and Chi-Him, T., "Control of voltage source inverter using multidimensional feedback quantization modulator," *IEEE Trans. Indust. Electron.*, Vol. 58, pp. 3027–3036, 2011.

[25] Sanbo, P., Junmin, P., and Zuohua, T., "A shifted SVPWM method to control DC-link resonant inverters and its FPGA realization," *IEEE Trans. Indust. Electron.*, Vol. 59, pp. 3383–3391, 2012.

[26] Odavic, M., Sumner, M., Zanchetta, P., and Clare, J. C., "A theoretical analysis of the harmonic content of PWM waveforms for multiple-frequency modulators," *IEEE Trans. Power Electron.*, Vol. 25, pp. 131–141, 2010.

[27] Turner, R., Walton, S., and Duke, R., "Robust high-performance inverter control using discrete direct-design pole placement," *IEEE Trans. Indust. Electron.*, Vol. 58, pp. 348–357, 2011.

[28] Yiqiang, C., Mwinyiwiwa, B., Wolanski, Z., and Boon-Teck, O., "Regulating and equalizing DC capacitance voltages in multilevel STATCOM," *IEEE Trans. Power Delivery*, Vol. 12, pp. 901–907, 1997.

[29] Ogata, K., *Modern Control Engineering*: Prentice-Hall, 1997.

[30] Samosir, A. S., and Yatim, A. H. M., "Dynamic evolution controller for single phase inverter application," *IEEE Symposium on Industrial Electronics & Applications (ISIEA 2009)*, pp. 530–535, Kuala Lumpur, Malaysia, 4–6 October 2009.

[31] Abrishamifar, A., Ahmad, A. A., and Mohamadian, M., "Fixed switching frequency sliding mode control for single-phase unipolar inverters," *IEEE Trans. Power Electron.*, Vol. 27, pp. 2507–2514, 2012.

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