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DEADBEAT-BASED PI CONTROLLER FOR STAND-ALONE SINGLE-PHASE VOLTAGE SOURCE INVERTER USING BATTERY CELL AS PRIMARY SOURCES

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ABSTRACT
This paper presents a deadbeat-based proportional-integral (PI) controller for stand-alone single-phase voltage source inverter using battery cell as primary energy sources. The system consists of the lead acid battery, third order Butterworth low pass DC filter and AC filter, H-bridge inverter, step-up transformer, and also a variety of loads as well as its sinusoidal pulse-width-modulation (SPWM) deadbeat-based PI controller. In this paper, two simulation case studies have been carried out which are the abrupt load changes from 400W resistive load to 500W resistive load and also from 400W resistive load to inductive load of 500W 0.85 power factor lagging. From the simulation results for both cases, the state-of-charge (SOC) battery is decreasing to supply power to the different type of loads, yet the battery voltage remains constant at about 36V and also the battery current exhibits smooth ripple despite current spikes produced by the H-bridge inverter so as to prolong the lifespan of the battery. It shows that the DC filter performs satisfactorily to isolate the current spikes generated by the SPWM controller and H-bridge inverter. Besides that, even though the load varies for both cases, the sinusoidal inverter output voltage can be tracked and maintained at $230V_{rms}$ with 50Hz frequency within few cycles from the instant the load changes as well as low THD_v content of 1.53% and 2.78% respectively. This indicates that the controller proves its robustness and stiffness characteristic in maintaining the output load voltage at desired value to supply the power for variety of loads with minimum THD_v.

Keywords: Stand-alone; single-phase inverter; deadbeat; battery cell; low pass filter; sinusoidal pulse-width-modulation.

1. INTRODUCTION

In last few decades, the traditional power generation methods of burning the primary fossil fuels such as coal, oil and natural gas affect the environment which causes an increase in greenhouse gas emissions that leads to global warming. Consequently, it becomes the driving force for the growing interest in alternative energy (Itoh & Hayashi, 2010; Lee, Song, Park, Moon, & Lee, 2008; Sangmin, Youngsang, Sewan, & Hyosung, 2007; Yaosuo, Liuchen, Sren Baekhj, Bordonau, & Shimizu, 2004). In order to reduce the environmental pollutions, sustainable energy electricity generation systems are gaining popularity and the development of distributed power generation (DG) systems as well as the stationary power generation stand-alone applications systems become more significant (Delshad & Farzanehfard, 2010; Haimin, Duarte, & Hendrix, 2008; Yaosuo, et al., 2004). DG systems can be defined as the implementation of various power-generating resources that are usually small modular devices close to electricity users, including wind turbines, solar energy systems, fuel cells, micro gas turbines and small hydro systems, as well as the relevant controlling/managing and energy storage systems (Sakhare, Davari, & Feliachi, 2004; Yaosuo, et al., 2004). These systems commonly constitute DC-AC converters or inverters as interface with the single-phase loads or sources (Yaosuo, et al., 2004).

The single-phase inverters can be used in power conversion from wide output variation of DC voltage into fixed AC voltage for stand-alone applications or injecting a sinusoidal AC current output following the grid voltage and frequency for grid-connected applications (Lee, et al., 2008; Yaosuo, et al., 2004). Besides that, the inverters also being used in output power quality assurance that demanding low total harmonic distortion (THD_v), pure sinusoidal voltage at the specific magnitude, low frequency deviation and voltage/current flickering as well as fast dynamic response under large variation in loads (Abdel-Rahim & Quaicoe, 1996; Deng, Oruganti, & Srinivasan, 2003; Kawamura, Haneyoshi, & Hoft, 1988; Keliang, et al., 2006; Sangmin, et al., 2007; Selvajyothi & Janakiraman, 2010; Xu, Zhao, Kang, & Xiong, 2008; Yaosuo, et al., 2004).

The battery inverter system is more preferable and more flexible to operate in stand-alone mode applications (Haimin, et al., 2008). The single-phase inverters in stationary battery cell power generation systems have been installed worldwide for the purpose in case of utility power failures, and are widely used in delivering backup power to the critical loads such as computers and life support systems in hospitals, hotels, office building, schools, utility power plants and even airport terminals as well as the communication systems (Abdel-Rahim & Quaicoe, 1996; Deng, et al., 2003; Kawamura, et al., 1988; Sakhare, et al., 2004; Selvajyothi & Janakiraman, 2010; Xu, et al., 2008).

In general, there are many methods in producing a low distortion output voltage. One of those methods is the optimum fixed LC compensators designed to minimize the expected value of the total THD_v, while it is desired to maintain a specific value of the power factor (Zobaa, 2006). Alternatively, series and shunt compensation or hybrid series active power filters (APF) can be employed for the elimination of harmonic when non-linear loads are connected to an inverter (Itoh & Hayashi, 2010; Varschavsky, Dixon, Rotella, & Moran, 2010; Zeng, Tan, Wang, & Ji, 2010). However, appropriate use of reactive shunt compensators and filters may increase the harmonic current contents as well as the voltage distortion in the feeders of the systems (Pomilio & Deckmann, 2007). Besides that, the use of pure capacitive compensator combined with source harmonics would degrade power factor and overload the equipment (Zobaa, 2006). In (Dixon & Moran, 2002), it is shown that series active filters in two-level PWM based inverters have disadvantages of high-order harmonic noise and additional switching losses due to high-frequency commutation.

In previous research works, there are many control techniques for producing pure sinusoidal output voltage with low THD_v and fast dynamic response. First, the conventional PI or PID controllers for the single-phase inverter are presented in (Delshad & Farzanehfard, 2010; Sangmin, et al., 2007). Many discrete-time methods developed by low cost microcontrollers have been discovered, such as repetitive-based control (Keliang, et al., 2006), sliding mode control (Wenguang, Jiangang, Utkin, & Longya, 2008) and deadbeat-based control (Kawamura, et al., 1988; Mattavelli, 2005) to enhance the characteristic of the inverter systems. Besides that, variety control approaches for inverter systems have been reported for instance, the internal-model control (IMC) (Xu, et al., 2008), multiple feedback loop control (Abdel-Rahim & Quaicoe, 1996), composite observers control (Haimin, et al., 2008; Selvajyothi & Janakiraman, 2010), neural network based control (Deng, et al., 2003) and fuzzy logic based control (Sakhare, et al., 2004). In fact, deadbeat control is one of the most attractive techniques for discrete-time control since it is able to reduce the state variable errors to zero in a finite number of sampling steps and to provide the fastest dynamic response for digital implementation which can be seen in (Kawamura, et al., 1988; Mattavelli, 2005).

In previous research work, most of the inverters are used in the DG system for grid-connected applications, but, the investigation of the stand-alone application is lacking. In this paper, a stand-alone voltage source inverter system using the battery cell as primary energy sources has been proposed by using a deadbeat-based PI controller to produce quality sinusoidal output voltage. This proposed inverter system illustrates a simple structure with only an output voltage sensor at the load side and demonstrates an excellent performance. The proposed single-phase inverter is suitable for residential power generation especially for stand-alone applications. The control technique also has strong robustness, excellent dynamic and static characteristics. In order to prolong the lifespan of the battery, the CLC DC filter should be used to mitigate the ripple currents in the stand-alone power generation systems instead of using DC active filter in (Itoh & Hayashi, 2010).

2. STAND-ALONE SINGLE-PHASE INVERTER SYSTEM

2.1 System Configuration

In this paper, a low voltage harmonics single-phase voltage source inverter system using lead acid battery as the primary sources and being controlled by deadbeat-based PI controller is proposed as shown in Figure 1. It shows the schematic circuit and the block diagram of the stand-alone single-phase inverter system that includes a lead acid battery which is the primary source, third order Butterworth low pass DC filter, H-bridge inverter power MOSFET, step-up transformer, third order Butterworth low pass AC filter and the loads. This inverter system will be simulated in Matlab/SIMULINK and most of the components used can be obtained in Matlab/SimPowerSystem simulation software. In general, the power delivered from the lead acid battery to the loads passes through few stages. First, the battery injects the power to the CLC DC filter instead of H-bridge inverter in order to isolate the high peak ripple current created by the switching of the inverter. Then, the DC input voltage will be converted to AC output voltage using SPWM switching scheme for H-bridge inverter and the output voltage is then boosted up via step-up transformer with its transformer ratio of 1:9.5833. The secondary AC voltage contains many harmonics due to the switching frequency of the inverter and it should be filtered out by using CLC AC low pass filter to produce 230 V_{rms} pure sinusoidal output voltage for loads in the stand-alone application systems. The magnitude and the frequency of the output voltage are controlled by using the deadbeat-based PI SPWM controller in the system with the feedback signal of the fundamental rms value of the output voltage.

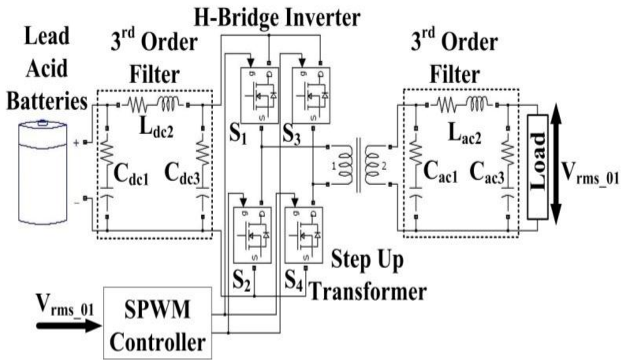

Figure 1 The schematic circuit and block diagram of the stand-alone single-phase inverter system

2.2 Lead Acid Battery Model

In this paper, the 36V, 120Ah lead acid rechargeable battery will be used as the primary energy source in the stand-alone single-phase inverter system. The initial state-of-charge (SOC) of the battery is considered to be 50%. The circuit diagram in Figure 1 shows the connection of lead acid battery in inverter system.

2.3 Third Order Butterworth Low Pass DC Filter Model

As reported in (Itoh & Hayashi, 2010), the input current ripples will shorten the lifespan of electrolytic capacitors, batteries and fuel cells that act as the primary sources. Therefore, the lead acid battery needs to be connected to a third order Butterworth low pass DC filter in order to protect the battery from getting damage. The DC filter components constitute two capacitors and an inductor. These components have a transfer function that can be realized using Cauer 1-form. The *k*th elements of the filter components can be expressed as (Timar & Rencz, 2007):

$$C_K' = 2\sin(\frac{2k-1}{2n}\pi), k = odd \quad (1)$$

$$L_K' = 2\sin(\frac{2k-1}{2n}\pi), k = even \quad (2)$$

where *n* is the number of passive components, C_k' is the *k*th capacitance value for the prototype and *k* is in odd number, meanwhile, L_k' is the *k*th inductance value for the prototype and *k* is in even number. Then, the DC capacitance and inductance value, C_{dc1}, L_{dc2}, and C_{dc3}, as indicated in Figure 1 can be calculated with the aid of frequency and impedance scaling technique as expressed below (Kaufman, 1982):

$$Z = \frac{V^2}{P} \quad (3)$$

$$C_k = \frac{1}{Z\omega_c} C_K' \quad (4)$$

$$L_K = \frac{Z}{\omega_c} L_K' \quad (5)$$

where *Z* is the terminating impedance in *Ω* and ω_c is the cut-off radian frequency with $\omega_c = 2\pi f_c$ and f_c is the cut-off frequency. In the simulation model, the capacitance and inductance values for the DC filter for C_{dc1} and C_{dc3} are 872 µF and L_{dc2} is 5.8mH.

2.4 Single Phase Inverter Model

In (Yaosuo et al., 2004), an overview of single-phase inverters topologies developed for small distributed power generators were discussed. There are many types of the inverter topologies. However, the traditional buck inverter and line frequency transformer shows a simple circuit topology and low components counts, leading to low cost and high efficiency. Such a system also demonstrates robust performance and high reliability shown in (Yaosuo, et al., 2004) that is totally agreed in (Sangmin, et al., 2007) as depicted in Figure 1. It indicates the simple H-bridge voltage source inverter that can be used for conversion from DC to AC voltage, supplying the power to the loads. It is used to produce and regulate the sinusoidal output voltage at rms value of 230 V_{rms} with 50 Hz frequency to a various type of loads in stand-alone power generation system.

2.5 Deadbeat-based PI controller with SPWM Switching Control Scheme

In order to maintain and regulate the output voltage at 230 V_{rms} for different type of loads with 50 Hz constant frequency, a deadbeat-based PI controller with SPWM switching control scheme is proposed and employed in the single-phase inverter in stand-alone power generation system as shown in

Figure 1. The fundamental rms value of output voltage at 50 Hz at the terminal load, V_{rms_01}, will be fed back to the controller and compared with the reference signal of 230 V_{rms}. The difference between two signals is then input to a PI controller to get the corresponding and appropriate modulation index which is accumulated from time to time after a time delay. Next, the product of the previous modulation index with two sinusoidal signal references which are 180° out of phase from each other will be compared with the triangular signal waveforms in order to produce SPWM switching waveforms used to trigger the four power MOSFETs, S_1, S_2, S_3 and S_4 of the H-bridge inverter. The sinusoidal signal waveforms that have been used as reference having constant 50 Hz, meanwhile; the switching frequency of the triangular signal is 5 kHz. Hence, using this simple controller triggering the MOSFETs as shown in Figure 1, the smooth sinusoidal output voltage of 50 Hz can be regulated and maintained.

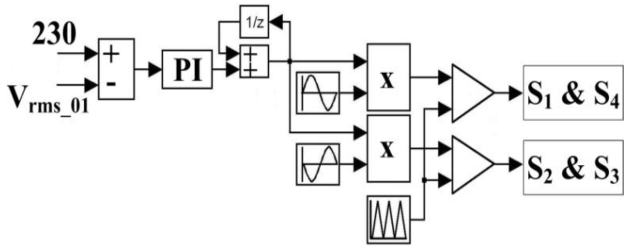

Figure 1 The block diagram of deadbeat-based PI controller with SPWM switching technique

2.6 Step Up Transformer Model

As depicted in Figure 1, a step-up transformer is connected after the H-bridge inverter to increase the primary voltage in order to maintain the output voltage at 230 V_{rms}. The transformer turn ratio in this simulation is 1:9.5833. This approach of using transformer is preferable because it can act as isolation transformer to prevent the inverter system from the surge as well as noise mitigation.

2.7 Third order Butterworth Low Pass AC Filter

After boosting the primary voltage using step-up transformer, the secondary output voltage consists of many distortion as well as harmonics. Therefore, a third order Butterworth low pass CLC AC filter should be connected before sending power to the loads so as to filter out the unwanted. The calculation for C_{ac1}, L_{ac2} and C_{ac3} as indicated in Figure 1 are based on the expressions from (2) to **Error! Reference source not found.**. In the simulation, the capacitance and inductance values for the AC filter that have been used for C_{ac1} and C_{ac3} are 31 µF and L_{ac2} is 0.334 H.

3. SIMULATION RESULTS AND DISCUSSIONS

This deadbeat-based PI controller proposed to produce low voltage harmonic with constant frequency of 50 Hz and to maintain constant rms output voltage of 230 V_{rms} in pure sinusoidal waveform at the terminal load for various type of loads is simulated in Matlab/Simulink software. In the simulation, the sampling time used is 2 µs for the robustness and stiffness of the simulation. Figure 3 and Figure 4 are showing the SPWM gate signals of S_1 and S_4 as well as SPWM gate signals for S_2 and S_3 that have been produced by comparing the 50 Hz reference sinusoidal waveforms and 5 kHz triangular waveform respectively whereby one of the sinusoidal waveform is 180^0 out of phase from the other one, assuming that the modulation index is 1.00. In fact, the modulation index of the inverter system keeps changing due to the existence of deadbeat-based PI controller.

In the simulation, there are two types of load change have taken place. First, Figure 5 to Figure 8 show the simulation results for the case when the resistive load is changing from 400W to 500W. Figures 5, 6 and 7
Figure 4show the SOC, battery voltage and battery current when the load changes respectively. During the simulation time, the SOC of the battery is decreasing, so, the battery is discharging from the beginning of the simulation linearly. Meanwhile, the battery voltage is almost constant at 35.7 V with significant ripples and on the other hand, the battery current is in the range for 18 A to 26 A. It shows smooth ripples instead of spiking current produced by the H-bridge inverter MOSFETs due to the components of the DC low pass filter as shown in Figure 1. This can protect the battery from malfunction in a short time. Besides that, Figure 8 shows the output voltage and output current at the load terminal when the load changes respectively. During the step response of the load changes, the output voltage which initially stays at 230 V_{rms} experiences sudden decrease in magnitude and slowly ramps up to 230 V_{rms} within four cycles. In addition, it shows a very good sinusoidal output voltage even though the sudden change in loads whereby the THD_v of the last two cycles of the inverter output voltage is also only 1.53 %. This indicates that the AC filter exhibits good performance in filtering out the unwanted frequency components. The phase of the output voltage is the same as the phase of the output current since the step change occur within purely resistive load. Hence, the deadbeat-based PI controller is operating satisfactorily to maintain the inverter output voltage magnitude at 230 V_{rms} with low voltage harmonics.

Secondly, Figures 9-11 indicate the simulation results for the case when the connected load is changed from resistive load of 400W to inductive load of 500W with 0.85 power factor lagging. Figures 9-11 demonstrate the SOC, battery voltage and battery current during the load change respectively. It can clearly be seen that the battery is in discharging mode in order to deliver power to the load by observing the SOC is decreasing linearly which is almost the same as in Figure 5. In the meantime, the battery voltage is kept constant at about 35.7 V with negligible ripples and it is similar in Figure 6. Before the step load change is taking place, the ripple waveforms are similar in Figure 6 and Figure 10 , however, after the load changes in both cases, the ripple waveforms are different due to the connected inductive load. As can be observed, the terminal current of the battery exhibits smooth ripples instead of the spiking currents which prove excellent performance of the low pass DC filter. Besides that, the output voltage and output current at the load during the occurrence of abrupt load changes can be seen in Figure 12. Initially, the output voltage is 230 V_{rms} and during this transient, the magnitude of the output voltage decreases but it ramps up back to 230 V_{rms} again within four cycles. Similarly, the inverter output current shows same transient pattern as that of output voltage during this load change. Also, the magnitude of the inverter output current has increased due to higher load and lower power factor. Furthermore, smooth sinusoidal inverter output voltage can be seen although the inverter system is subjected to a sudden load changes. From the simulation, the THD_v of the last two cycles of the inverter output voltage is about 2.78 %, indicating high quality of filter components. With resistive load, the voltage and current waveforms should be in phase as shown in Figure 8, whereas the current should be slightly lagging the voltage as shown in Figure 12 when the load is partially inductive. From these results, the proposed deadbeat-based PI controller shows evidence of its robust characteristic to maintain the inverter output voltage magnitude at 230V_{rms} with low voltage harmonics even during the load is inductive at 0.85PF.

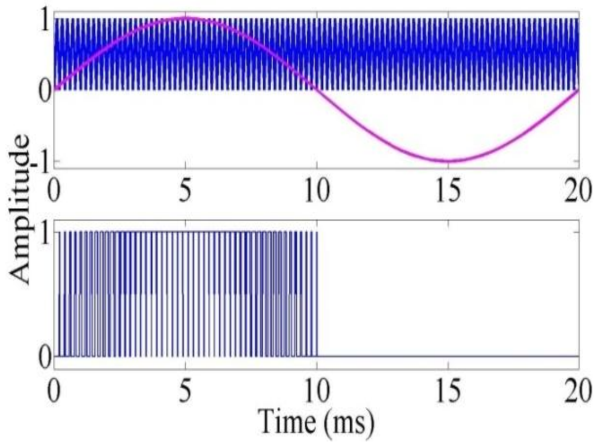

Figure 2 SPWM gate signals S_1 and S_4 produced by comparison of sinusoidal and triangular waveforms

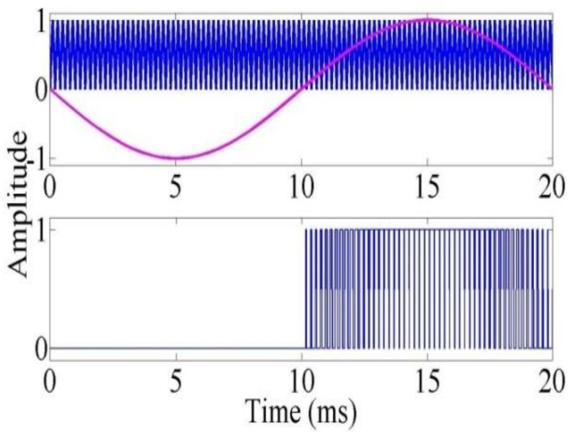

Figure 3 SPWM gate signals S_2 and S_3 produced by comparison of sinusoidal and triangular waveforms

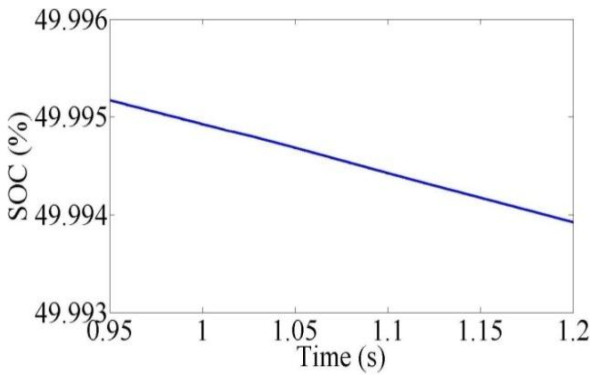

Figure 4 SOC of battery when the resistive load changing from 400W to 500W

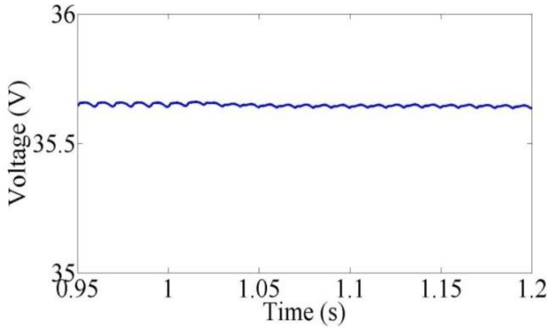

Figure 5 Terminal voltage of battery when the resistive load changing from 400W to 500W

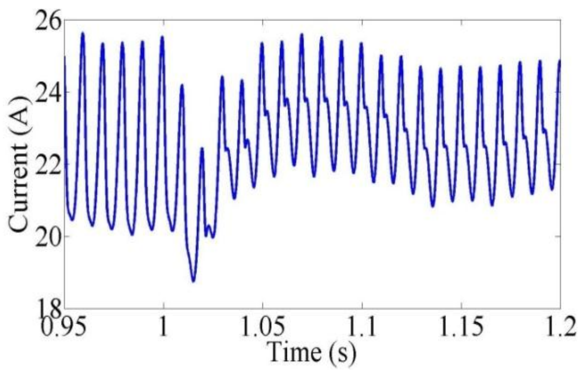

Figure 6 Terminal current of battery when the resistive load changing from 400W to 500W

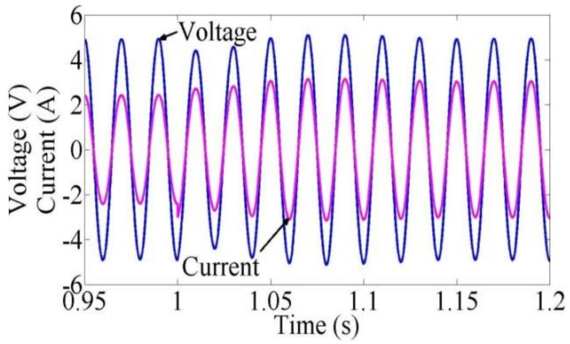

Figure 7 Output voltage and output current when the resistive load changing from 400W to 500W (Voltage: 65 V/div, Current: 1.0 A/div)

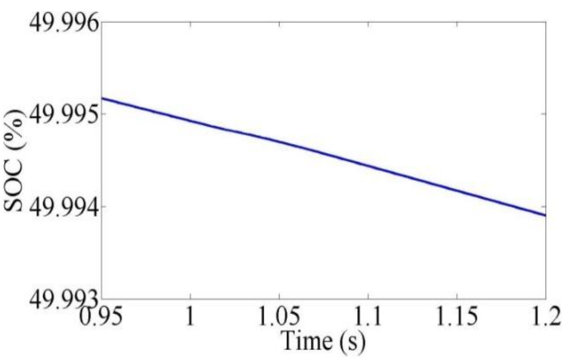

Figure 8 SOC of battery when the load changing from resistive load of 400W to inductive load of 500W with 0.85 power lagging

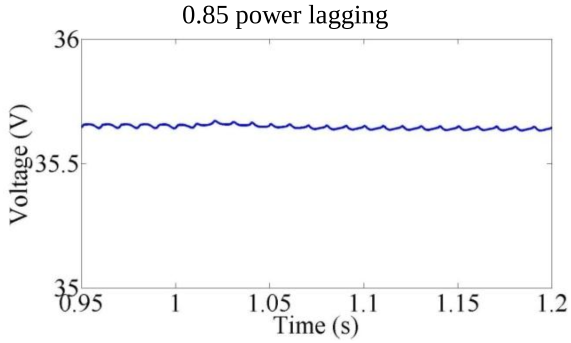

Figure 9 Terminal voltage of battery when the load changing from resistive load of 400W to inductive load of 500W with 0.85 power lagging

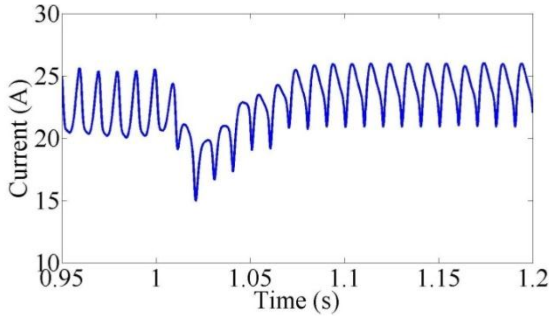

Figure 10 Terminal current of battery when the load changing from resistive load of 400W to inductive load of 500W with 0.85 power lagging

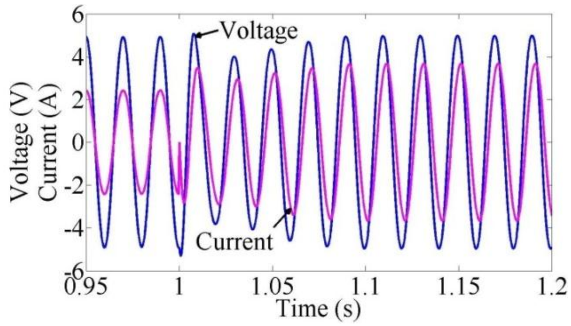

Figure 11 Output voltage and output current when the load changing from resistive load of 400W to inductive load of 500W with 0.85 power lagging (Voltage: 65 V/div, Current: 1.0 A/div)

4. CONCLUSION

A stand-alone single-phase voltage source inverter using battery cell as primary energy sources and being controlled by a simple deadbeat-based PI controller has been simulated in Matlab/Simulink software. It consists of the lead acid battery, third order Butterworth low pass DC filter, H-bridge inverter, step-up transformer, third order Butterworth low pass AC filter and also variety of loads as well as its deadbeat-based PI controller. From the simulation results, it shows a proper SPWM control switching scheme associated with the deadbeat-based PI controller has been generated to control the H-bridge inverter MOSFETs where its modulation index can be changed according to the feedback signal of the fundamental output voltage. Besides that, in the simulation of the load changes within purely resistive load, the battery is discharging to supply the power while the battery voltage is kept constant as well as the battery current has negligible spikes due to the well performing DC filter so as to extend battery lifespan. The output voltage also shows a good sinusoidal waveform of 230 V_{rms} with only 1.53% THD_v after the load changes and proves the controller exhibits fast dynamic performance as well as effective filter components. The output currents are in phase with the output voltage due to purely resistive load. Furthermore, in the case of load changes from resistive load to inductive load, the inverter is still able to produce sinusoidal waveforms with 2.78% THD_v, and the voltage is maintained at 230 V_{rms} within few cycles after being subjected to abrupt load changes. Hence, it proves that the deadbeat-based PI controller demonstrates a very good performance and acquires robust characteristic in tracking the output voltage at the desired value.

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