Modeling of single phase off-grid inverter for small standalone system applications

This paper presents the detail circuitry modeling of single phase off-grid inverter for small standalone system applications. The entire model is developed in MATLAB/Simulink platform using circuitry model. This off grid inverter consists of a high frequency DC-DC step up converter cascaded with a full bridge PI control voltage source inverter using SPWM modulation with LC filter to produce sine wave output. This is a common design used in many small commercial off-grid inverter. This off-grid inverter model is capable to produce AC sinewave output voltage at 230 V 50 Hz up to 1 kW power from a 48 V DC lead acid battery source. The AC sine wave output waveform achieved a voltage Total Harmonic Distortion (THD) of less than 1 % which is almost a pure sine wave. The conversion efficiency performance of the off-grid inverter achieved more than 94 %. The performance of the model is validated by real commercial off-grid inverter. The performance validation experiment shows that the off-grid inverter Simulink model conversion efficiency and THD performance are comparable to the commercial off-grid inverter. This model contributes to assist small to medium standalone system load and battery sizing design with greater accuracy.

1. INTRODUCTION

In the past decade solar photovoltaic renewable energy has gained an exponential growth around the globe up to 181 GW installed worldwide as of the end of 2018 [1]. The is because the ease of installation and less maintenance due to no moving part involves in the photovoltaic system, besides that, the cost of the photovoltaic system has been reduced significantly throughout the years are that major factors that favour photovoltaic system as popular choices in the renewable energy industry. Power inverter is a power electronics converter that converts DC input voltage to AC output voltage with controlled output voltage magnitude and frequency. The inverter plays an important role in the renewable energy chain, it is an indispensable parts of solar photovoltaic and battery energy storage system. Inverter has basically divided into three distinct categories, there are grid connected inverter, off-grid inverter and On/Off Grid Tie Inverter.

Each inverter has there are own challenges. The off-grid inverter basically uses in standalone system; the main challenges are to step up low DC battery voltage to AC supply voltage level in either single or three phase. It must be capable to maintain the AC output voltage magnitude and frequency under various load conditions within it rated power capacity. On the other hand, the grid connected inverter requires the synchronization of phase, frequency and magnitude with the utility grid in either single or three phase. Apart of grid synchronization, it is also required to control the delivery of real and reactive power as well as ride through capability during fault. It must also be capable to disconnect itself from the grid when islanding event occurred. Lastly, the On/Off Tie inverter is capable of operates in both islanded and grid connected conditions of a microgrid. The earliest written record of the term “inverter” can be traced back to 1925 when D.C. Prince published an article entitled “The Inverter” in GE Review. However, the idea of converting DC to AC experiment was proposed and carryout by Alexanderson from GE in 1920, back then he called this process “inverted rectification”. Prince appears to have been borrowing Alexanderson expression of “inverter rectification” and created a single English-language word inverter that has been used since then till present day [2].

Off-grid inverter basically consists of 2 stages of converter, the DC to DC voltage step up converter and DC to AC inverter with voltage PI control and LC filter to produce sine wave output. Each stage has its own challenges and there are many works of literature has been published to address these challenges and research gap for the off-grid inverter. For the first stage, the DC to DC voltage step up conversion is carryout using the push-pull converter topology through a high frequency step up transformer and rectification. The high frequency push-pull converter topology has been commonly used as the first stages for many small to medium commercial off-grid inverter design. The challenges are to step up the low battery DC voltage level with minimum losses, low footprint and weight of the components. There are literatures proposed an interleaving push-pull converter which can produce high output voltage from a very low battery voltage input. The interleaved push-pull converter is a combination of multiple push-pull converters with transformer secondary rectifier connected in series for achieving the desired output voltage level [3-4]. The shortcoming is the cost, footprint and weight of this interleaved push-pull will increase with the number of transformers, switching devices and rectifiers. Another literature proposed to simplify the entire off-grid inverter by using only one stage of push-pull inverter to step up the voltage at switching frequency of 50 or 60 Hz. This significantly increases the size and weight of the transformer and the AC output waveform is highly distorted and no longer sine wave [5-6]. There are other approaches by utilizing single or dual DC-DC boost converter topology to step the battery voltage to the desired voltage level in place of push-pull topology [7-11]. This approach reduces the use of step up transformer and rectifier stage. However it suffers from low efficiency and voltage magnitude stability to step up battery 12 V to

350 V and above. The second stage is the DC to AC inverter where H-Bridge topology with either MOSFET or IGBT switching devices is commonly utilized. A Sinusoidal Pulse Width Modulation (SPWM) is use to switch the H-Bridge with LC filter to produce sinewave AC output waveform [12-13]. A PI feedback control is utilized for voltage or current control. There is literature proposed to have a very high switching frequency of 100 kHz for the push-pull inverter to step up the voltage followed by a 20 kHz SPWM switching frequency to switch the H-Bridge [14]. However, PI feedback control was not included in the off-grid inverter design and high switching frequency suffer from high switching losses. The off-grid inverter feedback control presented in the literatures [15-19] assumed a constant voltage source and multi-level DC link [20-21] is supply to the HBridge which does not reflect the actual inverter operation with battery. The inverter H-Bridge plant and system tracking response were not discuss for the PI controller design [22-27].

In summary the above literatures lack of performance analysis including conversion efficiency, total harmonic distortion and validation with reference to commercial off-grid inverter. The modeling details are not provided to make simulation reproducible. This paper intended to present the modeling of a complete single phase off-grid inverter commonly implements in commercial inverter. It consist of a DC-DC 20 kHz high frequency step up converter and a H-Bridge inverter with 500 Hz SPWM and voltage PI feedback control.

2. RESEARCH METHOD

The entire off-grid inverter model is developed using MATLAB/Simulink platform with Simscape Electrical blocksets. The completed model is then tested and simulate under Simulink environment for performance analysis. The complete overview of the off-grid inverter model in Simulink is shown in Figure 1. It consists of a battery source, DC-DC step up converter, full bridge inverter with voltage PI control and a resistive load. This is the common design use for many small to medium commercial off-grid inverter. The battery model is directly obtained from Simulink Simscape Electrical blockset library and a resistive element is used to represent the inverter load by setting its resistance value. The off-grid inverter model is capable of converting a 48 VDC from a battery source to 230 VAC 50 Hz up to 1 kW power rating. The following sections explain the circuitry model in details.

2.1. DC-DC step Up converter

The DC-DC step up converter steps up the battery source 48 VDC to 400 VDC. The DC-DC step up converter utilizes the high frequency push-pull converter to converts the battery source 48 VDC to 48 VAC at 20 kHz and step up through a high frequency transformer to 400 VAC and then rectified it back to 400 VDC. The detail circuitry model of the DC-DC step up converter section is shown in Figure 2. The push-pull converter uses two MOSFET switches arrange in push-pull topology connect to the center tap high frequency transformer. The MOSFET Ron is set to 0.05 Ω. The MOSFET is switch by a pulse generator with 20 kHz switching frequency at 50% duty cycle. The NOT block provide the 1's complement output of the pulse generator. The two MOSFET in the push-pull topology is switch in a complementary manner to push and pull the current through the center tap transformer to produce 20 kHz AC output. The 2000 μF input capacitor serves to smooth out the inrush current to the transformer during switching. The high frequency center tap transformer nominal power and frequency is set to 5 kVA and 20 kHz respectively. The magnetization resistance and inductance of the high frequency step up transformer is set at 5000 and 500 pu respectively. By taking account of the voltage drop across the MOSFET during switching both primary winding 2 and 3 that form the center tap is set to 46 Vrms. The secondary winding 1 is set at 400 Vrms. The high frequency transformer significantly reduces its physical footprint and weight compared with low frequency transformer with similar power rating. This is a very important criteria for off-grid inverter hardware implementation.

2.2. Full bridge inverter with voltage PI control

The full bridge inverter converts the DC output voltage from the full bridge rectifier to AC sine wave output. The full bridge inverter with voltage PI control in Simulink is shown in Figure 3. The full bridge inverter is implemented using the universal bridge block from the Simulink Simscape Electrical blockset library. In the universal bridge block, the number of the bridge is set to 2 and the power electronic device is set to MOSFET so that the universal block will configure as four MOSFETs H-Bridge circuit. The H-Bridge is switch and driven by Sinusoidal Pulse Width Modulation (SPWM). The SPWM modulator carrier frequency is set to 500 Hz. The output of the H-Bridge is then filtered through a LC low pass filter to produce a sine wave output waveform. The LC low pass filter is designed based on butterworth filter design. The inductor and capacitor are set to 0.1 H and 100 μF respectively. The output rms voltage of the inverter is then fed back to a PI controller. The reference voltage for the PI controller is set to 230 Vrms. The output of the PI controller is fed to the SPWM modulator through 2-Level PWM Generator block.

The PI controller gain was determined by the transfer function tuning method available in the PID block. The H-Bridge inverter plant model was identified with the data driven method. Two seconds of input and output data were simulated for model identification. With the availability of the single pole plant model, the PI controller was tuned to track as close as possible with the plant response [28]. With that in mind, the PI controller Kp and Ki were set to 0.0041 and 0.0288 respectively. The tracking performance achieved with almost no overshoot and attaining a settling time of 0.46 s. The identified plant model transfer function and tuned tracking response are shown in Figure 4.

The voltage Total Harmonic Distortion (THD) is the most important indicator to quantify any inverter AC output waveform with respect to ideal pure sinewave. The THD delivered from the grid is strictly governed by electrical utilities around the world. In general, the inverter voltage THD has to be less than 5% from IEC or IEEE standard perspective to be considered acceptable [29-30]. Mathematically the voltage Total Harmonic Distortion can be determined in (1) where V is the voltage magnitude and n is the harmonic order.

The instantaneous output voltage THD measurement provides a quick indication of the inverter output waveform performance. It is computes by the THD block based on (1) as shown in Figure 3. The THD block is fed in from the voltage measurement block taken at the output of the inverter. Since the THD block only output from 0 to 1 so a gain block with 100 is required to convert it to percentage.

3. RESULTS AND DISCUSSION

The completed off-grid inverter model is simulated in Simulink environment for performance analysis. The Simulink configuration is the most important aspect to ensure the test and simulation can be executed successfully. The Simulink configuration setup is configured to ode23tb (Stiff/TR-BDF2) solver with variable step. The simulation type is set to discrete with a sample time of 2.5 µs per sample. The following sections detail out the performance analysis of the model including output voltage tracking response and inverter efficiency performance validation with a commercial off-grid inverter.

3.1. Output voltage tracking stability

The output voltage tracking determines the off-grid inverter model output voltage stability and the performance of the tuned PI controller to maintain the set output voltage level of 230 V. Figure 5 shows the off-grid inverter model output voltage magnitude tracking stability. It can be clearly seen that the PI controller are able to track the output voltage between 227.2 V and 232.9 V, which are -1.22 % and +1.26 % of 230 V respectively. In summary, the tuned PI controller are able to track at the average output voltage of 230.4 V in less than 0.5 s without any overshoot.

3.2. Model performance validation with commercial inverter

To validate the performance of this Simulink model is comparable with the commercial off-grid inverter. A commercial off-grid inverter is setup with 48 VDC battery source and various AC loads is shown in Figure 6. The commercial off-grid inverter use for validation is from EPEVER SHI1000-42, the specification of the off-grid inverter power rating is 1000 W, THD of ≤3 % and efficiency of ≥94 %. The inverter is set to output 230 V 50 Hz. The lead acid 12 V battery is deep cycle gel type from OUTDO with a capacity of 100 AH and internal resistance of 4 mΩ at full charge. The 48 V battery source consist of eight 12 V battery connected in series of four batteries and parallel of two series set yield a total 48 V of 200 AH capacity with a total internal resistance of 8 mΩ. The AC loads in the validation experiment are 1 HP aircon and ten 100 W light bulb with dimmer control. The off-grid inverter Simulink model efficiency performance is carryout by simulating the inverter under various load condition ranging from 25 W to 1000 W with 230 V 50 Hz in Simulink environment. The efficiency can be determined by the ratio of the input power from the battery to the output power to the load as shown in Figure 1. The efficiency display shows the output power, input power and the conversion efficiency with a one second average window through the mean block.

Similarly, the efficiency performance for the commercial off-grid inverter is carried out by energizing the light bulb loads ranging from 25 W to 1000 W. The measured input, output power and efficiency are then save as reference for off-grid inverter Simulink model validation.

The conversion efficiency performance validation results are shown in Figure 7. It shows a common characteristic of many commercial inverter efficiency curves. The average efficiency from 500 W onward which is 50 % of rated capacity for the Simulink model and commercial inverter are 94.8 % and 93.8 % respectively. The efficiency drop significantly at load power less then 100 W, this is simply because the conversion losses in power electronic switching devices became more prominent in low power conversion which is less than 10 % of the inverter rated capacity. The differences in efficiency at less than 100 W could be possibly caused by different topology, components tolerance and switching losses.

The overall performance validation experiment begins with recording the commercial off-grid inverter battery input power, battery state of charge and AC output power with 1 HP aircon load set at 26 °C running On and Off within the time interval of 60 mins. The recorded data is then saved as reference of the off-grid inverter Simulink model validation. The same battery source and AC load conditions are then applied to the off-grid Simulink model for 60 mins. The simulated data is then compared with the recorded data for validation and performance analysis. Figure 8 shows the overall validation results of output power, efficiency and battery state of charge. It can be clearly see that the power output of the model and commercial inverter almost overlapped with each other indicating the model simulation output power is close to the commercial off-grid inverter data. The conversion efficiency performance of the off-grid inverter model developed in Simulink is comparable with the commercial off-grid inverter recorded data near rated power which is around 900 W with an average efficiency around 94% which matches the commercial inverter product specification. When the aircon load is turn off, the load power is about 25 W where the average efficiency is about 50% which matches the efficiency performance curve shown in Figure 7, as explain earlier the differences in efficiency at 25 W of around 15% could be possibly caused by different topology, components tolerance and switching losses. The Battery State of Charge (SOC) discharge rate also shows a comparable trend with the real battery with about 1% of SOC difference at the end of the simulated data. The battery SOC oscillation is caused by the charge controller charging the battery when the aircon load is turn off. The validation experiment took place in the evening around 18:00 where there are still some evening sunlight to generate power from the photovoltaic panel to charge the battery. The slightly higher discharge rate of the real battery could be possibly caused by the aging of the battery and the different in SOC measurement method.

The off-grid inverter Simulink model results presented in this paper are fully reproducible, with that in mind the model in MATLAB/Simulink presented in this paper is made available by the authors for the reader to download at Mathworks official MATLAB Central File Exchange.

4. CONCLUSION

A detail circuitry modeling of an off-grid inverter model in Simulink is presented. Each stage of the off-grid inverter modeling are clearly illustrated and are fully reproducible. The off-grid inverter uses a 20 kHz high frequency transformer push-pull inverter to step up the battery 48 VDC to 400 VAC and convert back to DC through a full bridge rectifier. The 400 VDC is then converted to 230 VAC 50 Hz sinewave through H-bridge inverter with Sinusoidal Pulse Width Modulation and LC filter. The output voltage is control and maintains by PI feedback control. The off-grid inverter model is capable of converting a 48 V from a lead acid battery source to 230 V 50Hz up to a power rating of 1000 W. It achieved an average conversion efficiency of ≥94 % and produces sinewave output waveform with THD of less than 1 %. The performance of the Simulink model is also validated with the commercial off-grid inverter. The Simulink model presented can be flexibly changed to meet the commercial inverter with similar topology. This model contributes to assist small to medium standalone system load and battery sizing design with greater accuracy.

Comparison of Torque Control Strategies Based on the Constant Power Loss Control System for PMSM

7.1 INTRODUCTION

Variable speed permanent magnet synchronous machine (PMSM) drives are being rapidly deployed for a vast range of applications to benefit from their high efficiency and high control accuracy. Vector control of PMSM allows for the implementation of several choices of control strategies while control over torque is retained. The main torque control strategies for the lower than base speed operating region are zero d-axis current, maximum torque per unit current, maximum efficiency, unity power factor, and constant mutual flux linkages. In this chapter, these control strategies are compared based on the constant power loss (CPL) control system for PMSM. The CPL control system allows for maximizing torque at all speeds based on a set power loss for the machine. Comparison of different torque control strategies based on the CPL control system provides a basis for choosing the torque control strategy that optimizes a motor drive for a particular application. The application of the CPL control system for different categories of cyclic loads is also discussed in this chapter.

7.1.1 Background

High-performance control strategies are capable of providing accurate control over torque or speed to within a small percentage error. A high-performance control strategy can also optimize one or more performance indices such as torque, efficiency, and power factor over its operational boundary. The rated current and power usually define the operational boundary of the machine. This operational boundary is only valid at rated speed. However, researchers and practitioners carry the same operational boundary over to variable speed motor drives. Such a step is not necessarily correct, because the true operational boundary of a machine depends on the maximum permissible power loss vs speed profile for the machine.

The main torque control strategies for the lower than base speed operating region for PMSM are the maximum efficiency, maximum torque per unit current, zero d-axis current, unity power factor, and constant mutual flux linkages. The main control strategies for the higher than base speed operating region are constant back emf and six-step voltage. A comprehensive analysis and comparison of the torque control strategies in the operating region with lower than base speed is made in this chapter. Availability of such analysis and comparison is the key to choosing a control strategy that optimizes the operation of a particular motion control system. The torque control strategies are analyzed and compared based on the constant power loss concept that defines the operational boundary in each case. This study lays the foundation for the analysis of truly optimized motor drives for wide speed range motion control systems based on PMSM. Similar techniques can be applied to all types of motor drives.

7.1.2 Literature Review

The number of research papers that directly investigate the subject of operational limits of PMSM motor drives for variable speed applications is limited [1–9]. References [3, 4] deal with choosing motor parameters such that the motor is suitable for a given maximum speed vs torque envelope. References [2, 3] investigate the optimal design of a motor for delivering constant power in the flux-weakening region. Operating limits of PMSM are studied in [5, 6] based on the constant power criterion. Reference [7] studies the CPL-based operation of PMSM and compares the resulting operational boundary to that resulting from limiting current and power to rated values. An implementation strategy for the CPL control system is also provided in [7]. Reference [8] compares the constant back emf and six-step voltage torque control strategies based on the CPL operational boundary in the operating region higher than the base speed for PMSM. A detailed comparison of all torque control strategies for the full range of speed is given in [9].

For the lower than base speed operating region, one performance criterion can be optimized while torque linearity is being maintained at the same time. This degree of freedom can be utilized in implementing different torque control strategies. The main torque control strategies for PMSM for lower than base speed operating region are as follows:

(a) Zero d-axis current (ZDAC) (b) Maximum torque per unit current (MTPC) (c) Maximum efficiency (ME) (d) Unity power factor (UPF) (e) Constant mutual flux linkages (CMFL)

The ZDAC control strategy [10, 11] is widely used in the industry. It is similar to the armature controlled dc machine in that it forces the torque to be proportional to current magnitude in the

PMSM. The basics behind the MTPC control strategy have been known for several decades. The MTPC control strategy provides maximum torque for a given current. This, in turn, minimizes copper losses for a given torque [12]. However, the MTPC control strategy does not optimize the system for net power loss. The UPF control strategy [10] optimizes the system's apparent power (volt–ampere requirement) by maintaining the power factor at unity. The ME control strategy [13, 14] minimizes the net power loss of the motor at any operating point. The CMFL control strategy [10] limits the air gap flux linkages to any set or desired flux linkages. This control strategy, therefore, leads to a seamless flux-weakening strategy in the PMSM drive and is to be noted.

Each control strategy has its own merits and demerits. Reference [10] provides a comparison of the ZDAC, UPF, and CMFL control strategies from the point of view of torque per unit current ratio and power factor. The UPF control strategy is shown to yield a very low torque per unit current ratio. The ZDAC control strategy results in the lowest power factor. Reference [15] provides a comparison between the MTPC and ZDAC for an interior PMSM. This study shows that the MTPC control strategy is superior in both efficiency and torque per unit current as compared to the ZDAC control strategy. Torque is limited to rated value in all non-CPL-based control schemes for operation lower than base speed. The operating region below base speed is referred to as the constant torque operating region. It is shown in [7] that the maximum torque in the operating region with lower than base speed is not a constant. A thorough comparison of all five control strategies from the point of view of maximum torque vs speed profile provides a sound basis for choosing the optimal control strategy for a particular motor drive application.

Section 7.2 introduces the CPL control system in brief. Comparison of control strategies based on the CPL control system is described in Section 7.3. The application of the CPL control system to cyclic loads is presented in Section 7.4. The conclusions are summarized in Section 7.5. Section 7.6, the Appendix, provides the parameters of the prototype PMSM drive used in Section 7.2.

7.2 CONTROL AND DYNAMICS OF CONSTANT POWER LOSS BASED OPERATION OF PMSM DRIVE SYSTEM

The operational boundary of an electrical machine is limited by the maximum permissible power loss vs speed profile for the machine. The control and dynamics of the PMSM drive operating with constant power loss are presented in this section [7]. This control system is modeled and analyzed. Its comparison to a system that limits current and power, say to rated values, demonstrates the superiority of the CPL control system. The implementation of the CPL control system is given. This has the advantage of retrofitting the present PMSM drives with the least amount of software=hardware effort. The PMSM drives in this case then can use the existing controllers to implement any torque control criterion.

7.2.1 Rationale for Constant Power Loss Control

The maximum torque vs speed envelope for the control strategies for speeds lower than the base speed region is commonly found by limiting the stator current magnitude to the rated (or nominal) value. For speeds higher than base speed operational region, the shaft power is commonly limited to the rated value. Current limiting restricts copper losses but not necessarily the core losses. Similarly, limiting the shaft power does not limit power losses directly. Limiting current and power to rated values ignores the thermal robustness of the machine since that requires the total loss to be constrained to a permissible value. Rated current and power

7.2 CONTROL AND DYNAMICS OF CONSTANT POWER LOSS

guarantee acceptable power loss only at rated speed. Therefore, these simplistic restrictions are only valid for motion control applications requiring operation at rated speed. Increasingly, at present, single-speed motion control applications are being retrofitted or replaced with variable speed motor drives to increase process efficiency and operational flexibility. Also for cost optimization in manufacturing of the PMSMs, a few standardized lines of machine designs are utilized in vastly different environmental conditions, thus necessitating control methods to maintain the thermal robustness of the machine while extracting the maximum torque over a wide speed range. Only the CPL based operation can provide the maximum torque vs speed envelope from these viewpoints. A comparison of this operational boundary and the operational boundary resulting from limiting current and power to rated values clearly reveals that the CPL control system results in a significant increase in permissible torque at lower than rated speeds. Consequently, the dynamic response is enhanced below the base speed.