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Single-Phase Transformerless Line Interactive Uninterruptable Power Supply with Two Independent Control Algorithms

Single-Phase Transformerless Line Interactive Uninterruptable Power Supply with Two Independent Control Algorithms

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Abstract. This paper presents the development of two independent control algorithms for an Uninterruptable Power Supply (UPS). It is a mitigation tool to mitigate power interruption. The UPS circuit consists of a bidirectional buck-boost DC-DC converter, a rechargeable battery and a DC-AC/AC-DC converter. The bidirectional DC-DC converter has a function of charging (buck) or discharging (boost) the battery for maintaining DC-link voltage connected to the DC-AC/AC-DC converter. During the normal mode operation, the DC-AC/AC-DC converter supplies voltage to the bidirectional converter by performing AC to DC conversion. Instead, during the backup mode, the converter supplies voltage to the load by performing DC to AC conversion. In this work, a single-loop voltage control algorithm regulates the bidirectional converter. For the DC-AC/AC-DC converter, a multi-loop control algorithm regulates the output current using the inner loop and the output voltage using the outer loop. MATLAB/Simulink simulates the UPS to determine its performance during normal and backup mode operation. From the simulation results, both independent control algorithms can regulate the operation of both converters during both modes of operation. As a result, the UPS system is capable of supplying sinusoidal waveforms with low Total Harmonic Distortion (THD) of output current and output voltage. Both THD values are below 4%.

1. Introduction

Power quality issues have become the primary concern in power systems and electrical machines. It is essential to solving the problems by understanding and classifying them according to the magnitudes and durations of events. Figure 1 shows the classification of power quality problems based on the magnitudes and durations of events.

Based on the magnitude-duration plot, the magnitude of the events is described as a power interruption when the voltage magnitude is zero. However, when the voltage magnitude is below its nominal value, it is called an undervoltage problem. Instead, when the voltage magnitude is above its nominal value, it is referring to an overvoltage problem. Meanwhile, based on the duration, those problems can be classified as very short, short, long and very long power quality problems [1]. Nevertheless, this work focuses on mitigating interruption problem only.

There are some different standards of measuring the duration of the interruption. As examples, there are the European standard EN-50160 and the IEEE-1250 standard. According to the European standard, short interruption happens up to 3 minutes, and long interruption occurs longer than 3 minutes. Meanwhile, based on the IEEE standard, instantaneous interruption happens in between 0.5 and 30 cycles, momentary interruption is in between 30 cycles and 2 seconds, temporary interruption is in between 2 seconds and 2 minutes, and sustained interruption is longer than 2 minutes [1,2].

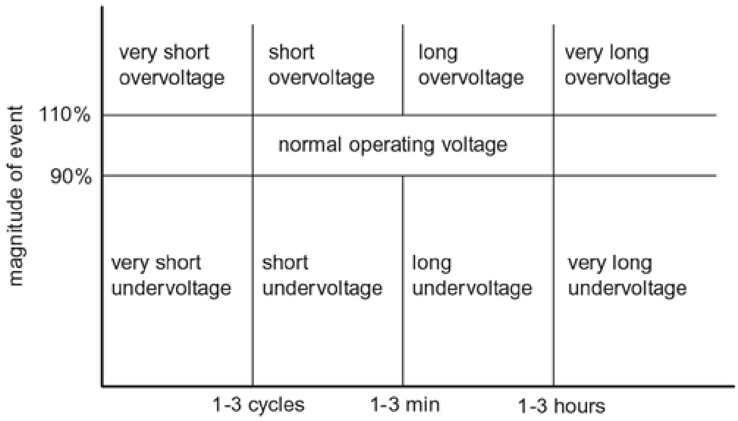

Figure 1. Magnitude-duration plot for classification of power quality events [1,2]

Power interruption may occur due to the failure of equipment, control system, fuses or breakers [1,2]. The effects of interruption become significant when it involved in the operation of sensitive devices used in factory production lines, security systems, banks and airport electrical systems [3]. Thus, the installation of a power generator with an Uninterruptable Power Supply (UPS) is vital to sustaining the operation of those sensitive devices. During the interruption, the UPS acts as a backup power supply before the generator resumes its operation. Based on the circuit configuration and operation, UPSs can be classified as online UPSs, offline UPSs and line-interactive UPSs.

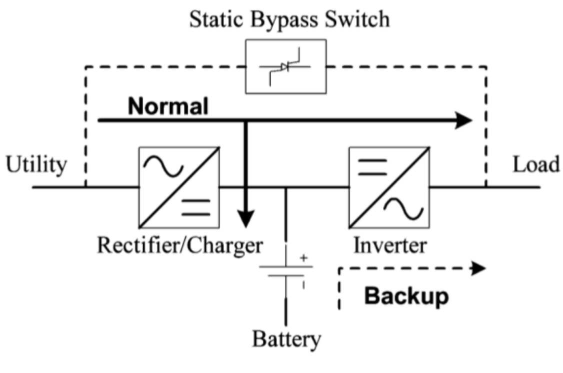

Figure 2. Block diagram of online UPS topology [5]

Figure 2 shows a block diagram of the online UPS system. It is also known as an inverter-preferred or a double conversion UPS. During normal mode, the rectifier/charger converts AC voltage to DC voltage and charges the battery. Then, the inverter converts the DC voltage to regulate the AC voltage supplied to the load. During a power failure, the battery supplies power to the load through the inverter. The advantages of the online UPS are providing isolation between the load and the main supply, and it is having very fast switching time. The main drawbacks are low efficiency, low power factor and high Total Harmonic Distortion (THD) [3,4].

A block-diagram of the offline UPS or line-preferred UPS or passive standby UPS is presented in Figure 3. During normal mode, the charger charges the battery while the utility side supplies power to the load directly. The inverter is in a standby mode to fed the load from the battery whenever power failure occurred. The advantages of the offline UPS are low cost, simple design and smaller size. The drawbacks are the load is directly fed by the utility without isolation and voltage regulation [3,4].

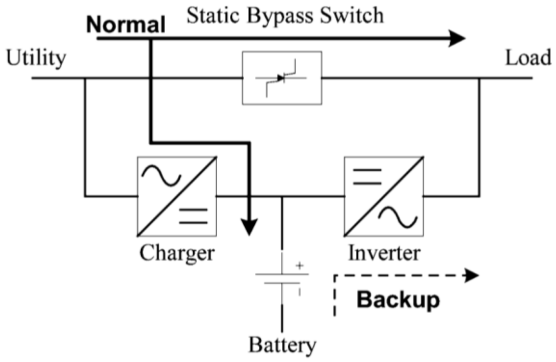

Figure 3. Block diagram of offline UPS topology [5]

The line-interactive UPS or parallel-processing UPS is an upgraded version of the offline UPS. Figure 4 depicts a block diagram of the line-interactive UPS. Based on the figure, the UPS consists of an inductor that connected in series to the utility side, and it is in parallel to the bidirectional converter and the load. During normal mode, the converter acts as a battery charger. Meanwhile, during a power failure, the converter acts as an inverter to supply the load from the battery. The UPS inherits the same advantages and disadvantages like offline UPS. Nevertheless, it has other pros, such as the capability to suppress input harmonic and compensate for small reactive power [5-7].

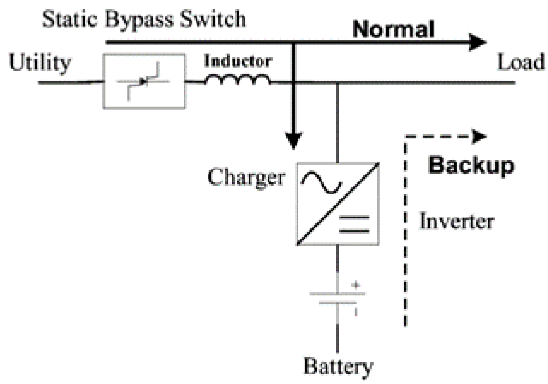

Figure 4. Block diagram of line-interactive topology [5]

In this research work, the line-interactive UPS is chosen due to its capability to suppress input current harmonics [5-7], low THD and simple design. Figure 5 and 6 show circuit topologies of the conventional and the proposed UPS system. Based on Figure 5, the circuit topology of conventional line-interactive UPS shows that the bidirectional inverter is operating with a line-frequency transformer. Hence, it may lead to high core losses and magnetic flux saturation [8,9]. Moreover, the transformer will increase the size of the UPS. Therefore, in order to improve the drawbacks from the transformer, the UPS will be redesigned by eliminating the line-frequency transformer by adding a bidirectional buck and boost DC-DC converter [11] as shown in Figure 6. By maintaining the DC-link voltage using the bidirectional buck and boost converter, the efficiency of the system can be improved [10,11].

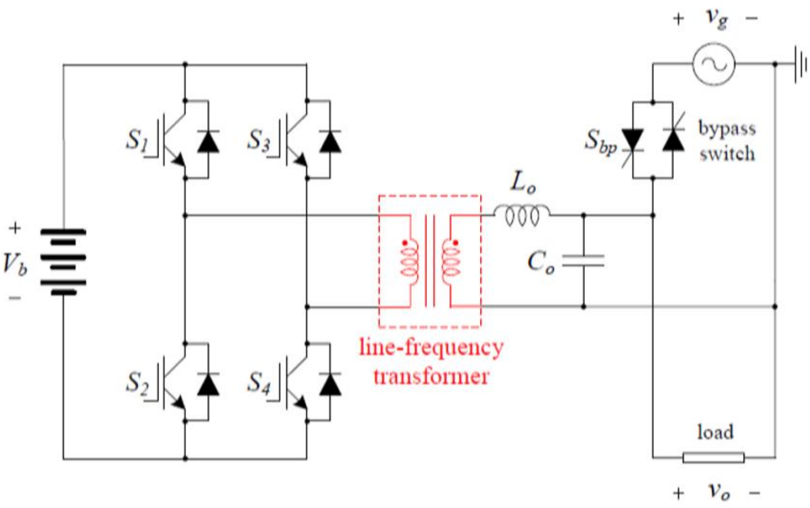

Figure 5. Circuit diagram of conventional line-interactive UPS [8]

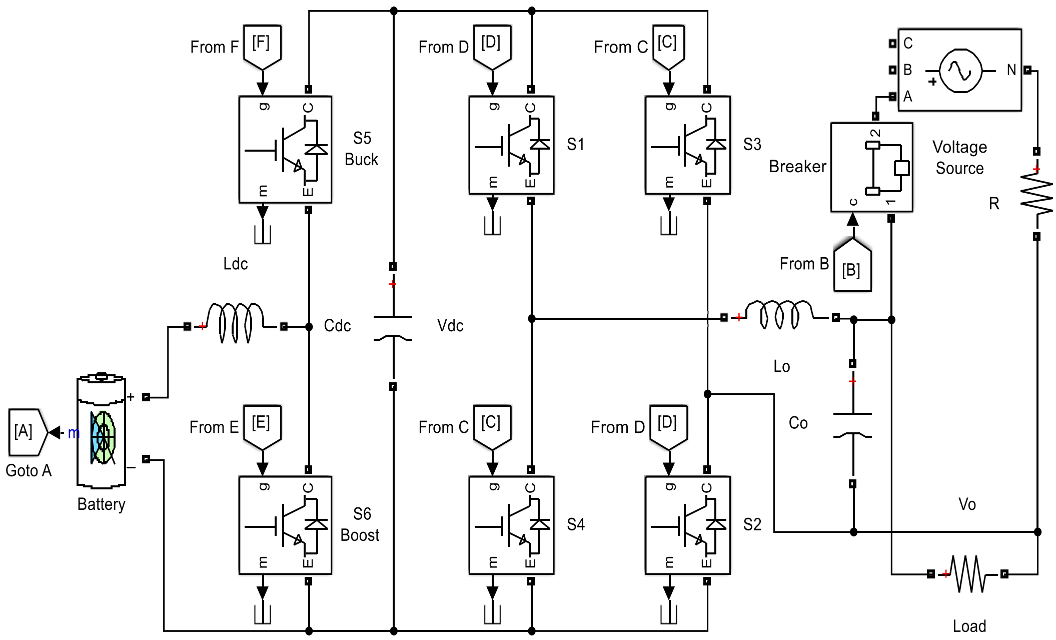

Figure 6. Circuit diagram of the proposed UPS

In [11], the single-phase line-interactive UPS employed a single-loop control algorithm to regulate the output voltage. Hence, it may affect the quality of the output current of the UPS; this concern does not discuss in the paper. Furthermore, the UPS in [11] does not utilise a battery. Instead, they used a fixed DC supply. Hence, in real practice, it is a challenge to work as a backup power supply. In this paper, a battery replaces the fixed DC supply in [11]. Thus, the study of battery performance can be conducted. Subsequently, this paper introduces a multi-loop control algorithm to control the output voltage and current of the UPS. Therefore, this paper can assess the quality of the output current in term of THD value. The multi-loop control algorithm is more favourable than a single-loop algorithm in achieving better UPS performance in overcoming voltage interruption [4].

2. Methodology

2.1. Overall Procedures

Figure 7 shows the overall procedures of this work. The process is started by designing a single-phase transformerless line-interactive UPS. It consists of a bidirectional DC-DC buck and boost converter, a rechargeable battery and a DC-AC/AC-DC converter. All converters in this system are constructed using IGBTs.

The bidirectional converter is regulated using a single-loop voltage control algorithm, while the DC-AC/AC-DC converter is controlled using a multi-loop voltage and current control algorithm. The tuning procedure for the controllers in the multi-loop control algorithm depends on the measured output voltage, V_o and the reference voltage, V_{ref}. Instead, for the controller in the single-loop control algorithm, it depends on the V_o value during normal and backup operation. The UPS utilise two switches to regulate the UPS according to normal mode or backup mode operation. The setting for the switches must ensure that the measured supply voltage, V_{ac} at the utility side follows the predetermined requirement.

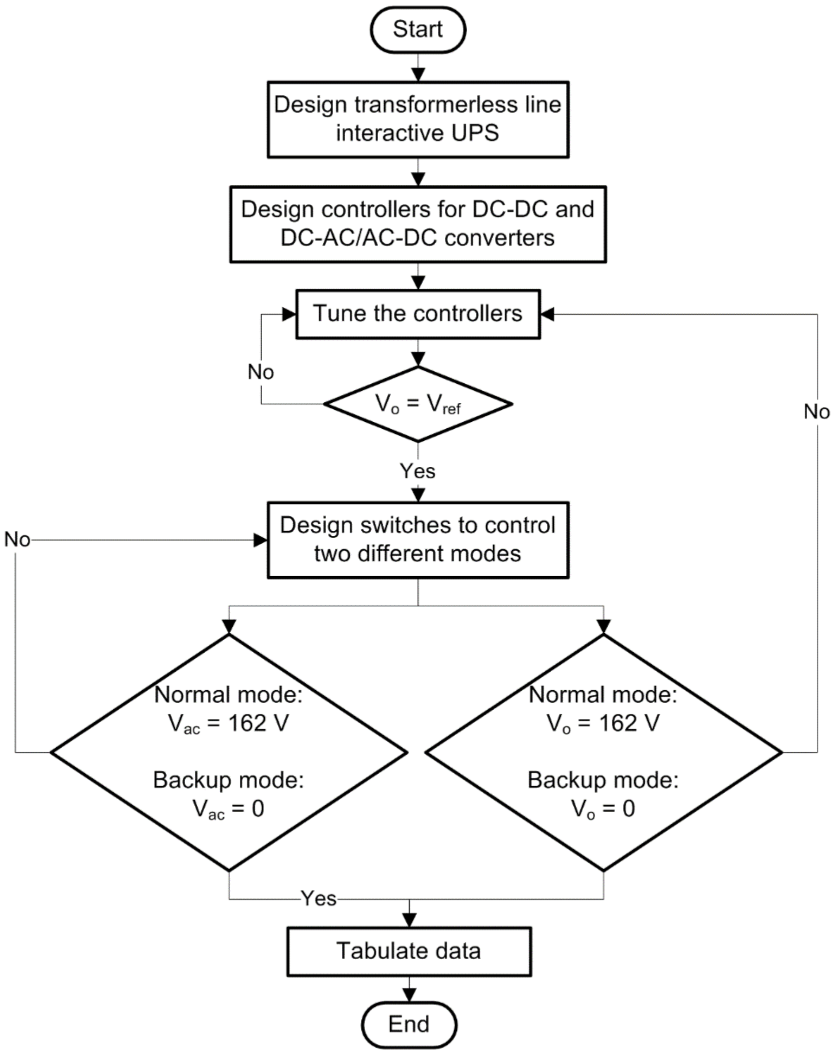

Figure 7. Flowchart of overall procedures

2.2. Single-loop Voltage Control Algorithm for Bidirectional Converters Operation

Figure 8 shows the single-loop voltage control algorithm architecture. In this work, a Proportional (P) controller is used to regulate the error signal between the actual average DC-link voltage, V_{dc} and the reference voltage value, $200V_{ref}$ [11]. This control algorithm generates two control signals: control signal at S5 is supplied to the buck converter for battery charging mode, and the control signal at S6 is supplied to the boost converter for battery discharging mode.

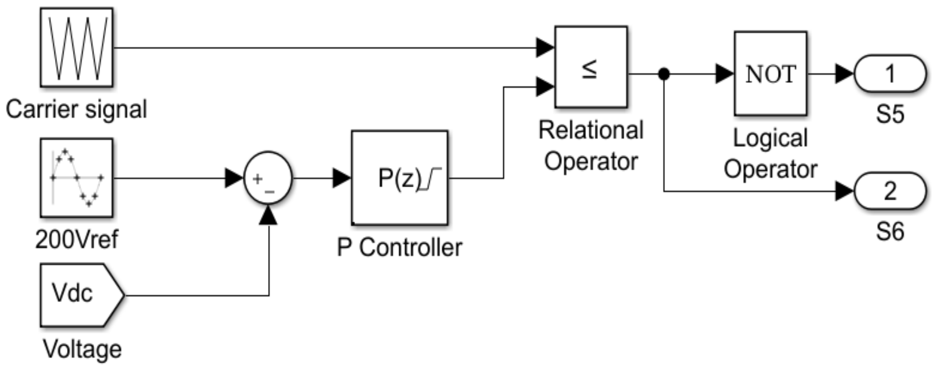

Figure 8. Block diagram of single-loop voltage algorithm for the bidirectional buck and boost converter

2.3. Multi-loop Voltage and Current Control Algorithm for DC-AC/AC-DC Converter Operation

Figure 9 shows a multi-loop voltage and current control algorithm. It is designed to control two different parameters as the feedback such as AC output current, I_o and V_o [11-13]. The outer loop is designed to regulate V_o based on the predetermined reference voltage value, $162V_{ref}$. Subsequently, the inner loop is designed to regulate Io based on the reference current signal, I_{ref} generated by the outer loop. This control algorithm employs a Proportional-Integral (PI) voltage controller for the outer loop and a P current controller for the inner loop. Hence, both voltage and current can be regulated simultaneously.

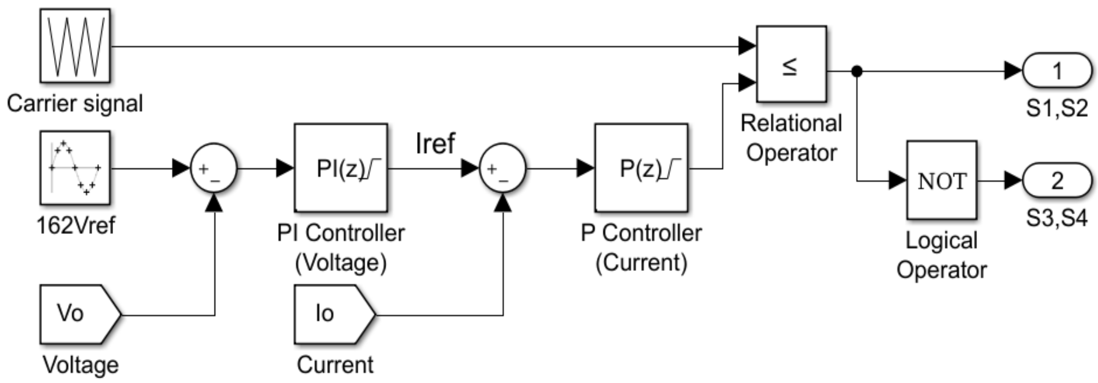

Figure 9. Multi-loop voltage and current control algorithm

2.4. Switch Control Design

In the proposed UPS system, both the buck and the boost converters will work separately. The buck converter will operate during the normal mode condition. In contrast, the boost converter will operate during the backup mode condition. Hence, a switch control algorithm is vital to determine which converter will work at a designated condition. Figure 10 presents the switch control algorithm. The switch control algorithm consists of two signal switches for the buck and the boost converters. The threshold of the switches is based on the generator status.

During normal mode, the load voltage is supplied by the grid. Meanwhile, during the backup mode, the UPS will replace the grid as a voltage supply to the load. As shown in Figure 6, a breaker is used to changeover both modes. The status of the breaker will affect the switch control signal. When the pulse generator and the breaker status are 1, the control signal produced by the single-loop voltage control algorithm will be applied on to the buck converter. Meanwhile, when the pulse generator and the breaker status are 0, the control signal will be applied to the boost converter. Switching signals generated by the switch control algorithm are depicted in Figure 11.

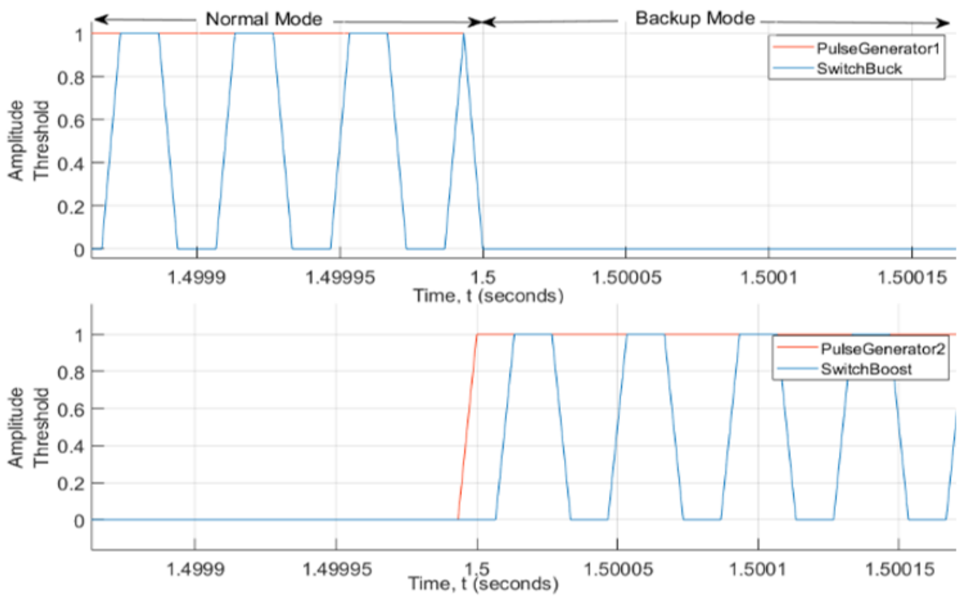

Figure 10. Block diagram of the switch controller

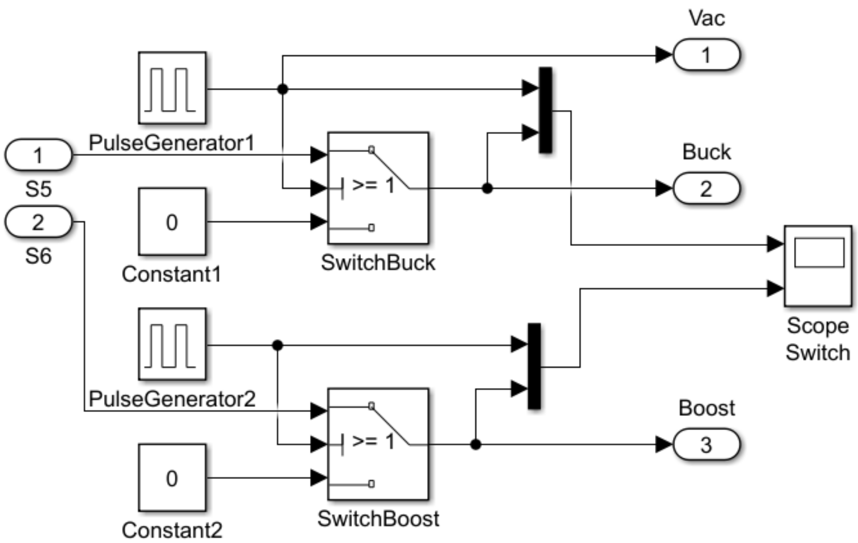

Figure 11. Switching signals of the switch control algorithm

3. Simulation Results and Discussions

MATLAB/Simulink simulates the UPS circuit and the control algorithms concurrently. Table 1 presents all parameters used in the simulation work.

Table 1. Parameters of proposed UPS

Parameters	**Values**
Input Voltage, V_{ac}	162 V
Output Voltage, V_o	162 V
DC-Link Voltage, V_{dc}	200 V
Battery Voltage, V_b	96 V
Inductor, L_b	330 µH
DC-Link Capacitor, C_{dc}	500 µF
Filter Inductor, L_o	15 mH
Filter Capacitor, C_o	330 µF

3.1. Effects of Variable Gain Values in Bidirectional Buck and Boost Converter Performance

This section discusses the effects of using variable P gain, K_p values in the single-loop voltage control algorithm. The assessment focuses on the performance of the bidirectional converter to maintain constant V_{dc} under that circumstance.

Table II tabulates the effect of using variable K_p values on the regulated V_{dc}. From the table, the relationship between K_p and V_{dc} is directly proportional to each other. These results show that the gain acts as a multiplier in the controller operation. Since the UPS needs to main 200 V of DC-link voltage; hence, the K_p for the P controller is 0.1.

Table 2. Effects of K_p to V_{dc}

K_p.	**V_{dc} (V)**
0.1	200
0.5	210
1.0	220
1.5	230
2.0	240

Figure 12 presents the V_{dc} waveform during normal mode and backup mode conditions when the control algorithm applied K_p of 0.1. In both conditions, the average V_{dc} value maintains at 200 V. The time taken by the P controller to react to the change of modes is 0.01 seconds. The result has verified the effectiveness of the control algorithm to regulate the bidirectional converter operation.

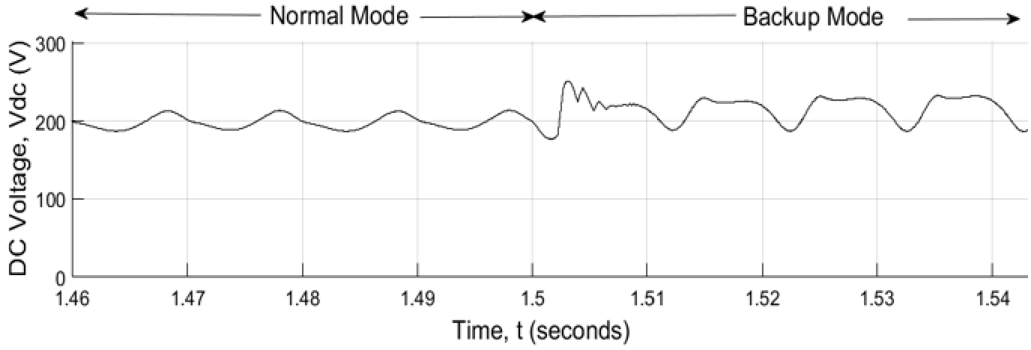

Figure 12. V_{dc} with K_p equals to 0.1

3.2. Effects of Variable Gain Values in DC-AC/AC-DC Converter Performance.

This section elaborates the effects of using variable K_p values in the multi-loop voltage and current control algorithm. It is based on the DC-AC/AC-DC converter to maintain its output AC voltage and current. Table 3 presents the results of using variable K_p values in the P voltage controller. From the table, when the K_p value increases, the peak values of V_o is 146.0 V. The values of V_o start to constant when K_p is 200. Thus, it needs support from another controller in the outer loop to increase the V_o value.

Table 3. Effects of variable K_p of the inner loop to V_o

K_p	V_o (V)
50	144.6
100	145.7
150	145.9
200	146.0
250	146.0
400	146.0

Next, a PI controller is added at the outer loop to enhance the results of the V_o. Table 4 showed the V_o value of the converter when the PI controller applied variable K_p values with zero K_i value. According to the table, the V_o value is also directly proportional to the K_p value. Based on the K_p value, the value of K_i is varied. The effect of verifying the K_i value on the converter operation is presented in Table 5. From the table, the Ki value of 5700 must be applied to allow the converter to generate162 V. Therefore, the chosen value of K_p of the P controller of the inner loop is 200. Then, the chosen values of K_p and K_i values of the PI controller of the outer loop are 20 and 5700, respectively.

Table 4. Effects of variable K_p of the outer loop to V_o

K_p	V_o (V)
5	158.5
10	160.3
15	160.8
20	161.2
25	161.3
50	161.5

Table 5. Effects of variable K_i of the outer loop to V_o

K_p	K_i	V_o (V)
20	4000	161.80
20	5000	161.93
20	5500	161.98
20	5600	161.99
20	5700	162.00

3.3. Operation of Proposed UPS

Figure 13 and 14 show waveforms of V_o and I_o supplied by the UPS to the load during normal mode (t = 0 seconds to t = 1.5 seconds) and backup mode (t = 1.5 seconds to t = 3.0 seconds). Additionally, Figure 15 presents waveforms of the State of Charge (SOC), voltage, V_b and current, I_b of the battery during both modes. SOC is used to determine the battery conditions: charging or discharging.

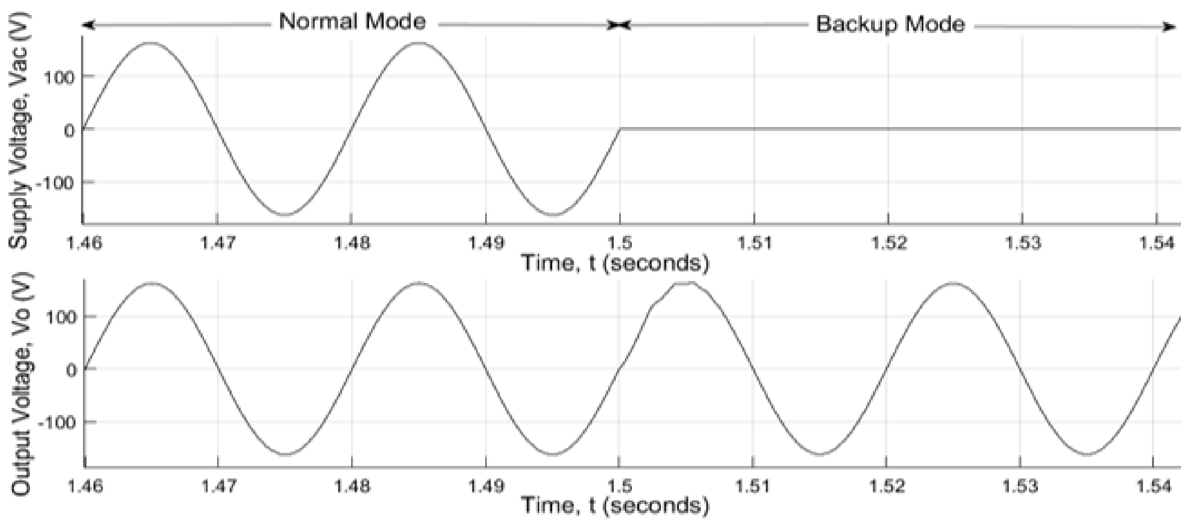

Figure 13. Waveforms of voltages after simulation with the proposed UPS

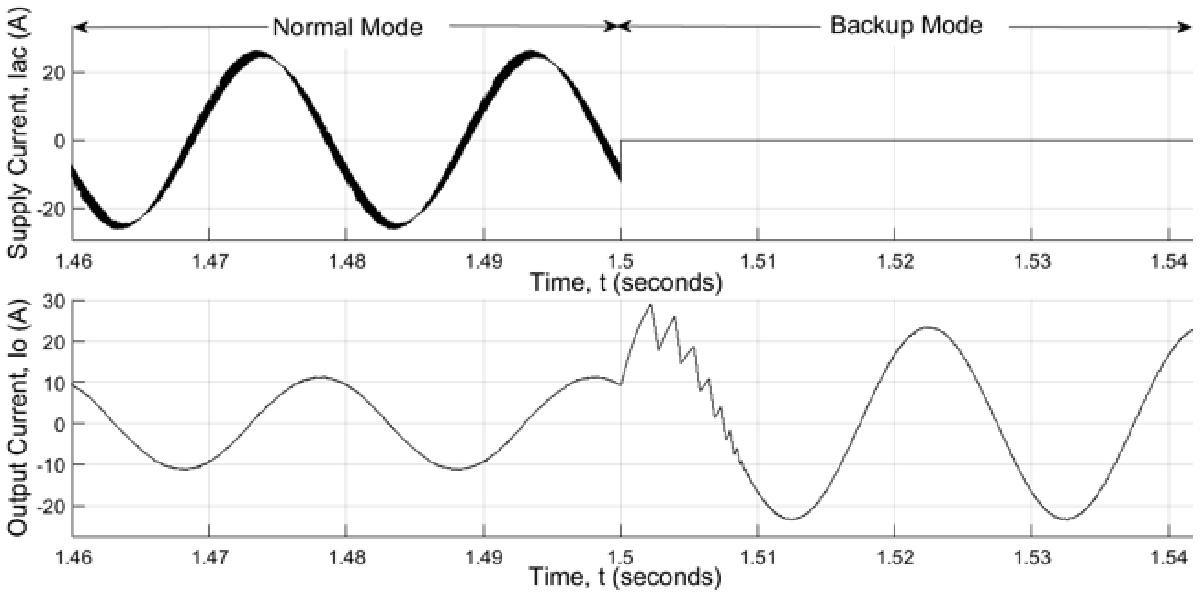

Figure 14. Waveforms of currents after simulation with the proposed UPS

Figure 13 shows that the grid is supplying AC voltage with the 162 V peak amplitude during the normal mode. At the same time, small current I_o is drawn by the UPS, as shown in Figure 14 for charging the battery. In Figure 15, the SOC waveform is increasing linearly. Hence, it indicates that the buck converter is in on-state for charging the battery. During this condition, the I_b has negative values as the current is flowing in the opposite direction; it flows towards the battery and not the load. For the V_b waveform, it is in a constant value of 130.5 V to maintain the DC voltage for backup supply to the load.

During the backup mode, Figure 13 has proven that the UPS is capable of supplying voltage at the peak amplitude of 162 V too. Also, Figure 14 shows the UPS also produces a sinusoidal waveform of I_o. Hence, it verifies the effectiveness of using the two independent control algorithms. Based on the figure, the UPS takes 0.01 seconds to reach its steady-state operation. From the Fourier Fast Transform (FFT) analysis, THD values of both V_o and I_o waveforms supplied by the UPS are below 4%. In Figure 15, the SOC waveform is decreasing linearly. Hence, it indicates that the boost converter is in on-state to discharge the battery. According to Figure 15, I_b has positive values as the current flows in the same direction of the supply to the load. Additionally, the amplitude of V_b reduces to show that the voltage is supplied to the load.

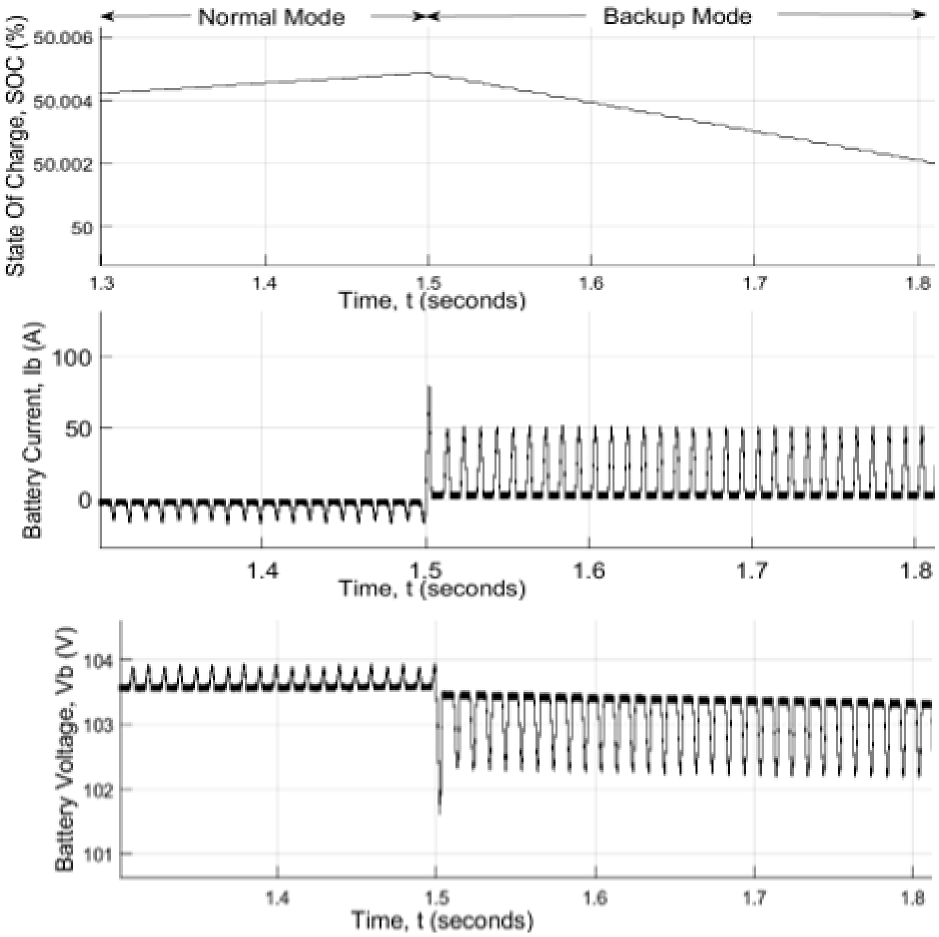

Figure 15. Waveforms of SOC, I_b, and V_b for battery after simulation with the proposed UPS

4. Conclusion
All simulation results have proven that the independent control algorithms are capable of regulating the operation of the single-phase transformerless line-interactive UPS. The effects of variable gains of both P and PI controllers are crucial to determine the suitable gain values for the controllers. Based on the selected gain values, the results show that the UPS can supply low THD voltage with the designated amplitude value. At the same time, the THD value of the supply current also low. Hence, it verifies that the implementation of the control algorithms has improved the performance of the UPS.

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