Novel Reduced Switches Single-Phase to Three-Phase On-line Uninterruptible Power Supply

Mehrnaz Sharifian[1] Mehdi Niroomand[2]

Abstract—This paper describes design considerations and performance analysis of a novel on-line single-phase to three-phase uninterruptible power supply (UPS) with reduced number of switches. The proposed topology uses only 5 active switches reducing the cost of the system compared to the traditional 10-switch topologies. The proposed UPS consists of a single-phase rectifier/charger, a two-leg/three-phase inverter connected to load, battery bank, DC link capacitor and an AC inductor. Detailed circuit operation and analysis as well as simulation results are also presented to verify its feasibility.

Keywords-Uninterruptible Power Supply (UPS); Single-Phase to Three-Phase Conversion; Reduced Switches

I. Introduction

Uninterruptible Power Supplies (UPS's) are nowadays indispensable equipment in supplying power to critical and sensitive loads. They protect sensitive loads against many existing disturbances in utility network like voltage variations, transients and harmonics. Applications of UPS systems include medical facilities, life supporting systems, data centers, emergency equipment, telecommunications and industrial processing systems.

Ideally, a UPS should deliver clean and uninterrupted power to the load, and at the same time draw sinusoidal, near unity power factor current from input supply. Additionally, static UPS's must be able to switch between utility and storage batteries as alternate energy sources. This switching must take place in zero or minimum time in order to avoid any malfunctioning of the supplied equipment. Other specifications like high reliability, high efficiency, low EMI and acoustic noise, electric isolation, low maintenance, low cost, weight and size must be also considered in a high performance UPS [1].

IEC-62040-3 standard classifies UPS's as passive-standby, line-interactive and double-conversion (on-line UPS). Each topology has its own characteristics and is used based on the load requirements and the severity and type of network disturbances [2].

The main advantages of a passive-standby UPS are its design, low cost and small size. The line conditioning is passive which makes this topology fairly robust. On the other hand, rather long switching time between standby and backup modes is the main disadvantage of this topology.

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The line-interactive topology has simple design, fairly high reliability and lower cost, and thus is becoming more attractive as compared to the double-conversion solutions. Since there is just a single stage conversion in this topology, the efficiency is inherently higher than that of the double-conversion UPS. The main disadvantage is the fact that there is no output voltage conditioning during normal mode because the inverter is not connected in series with the load [3], [4].

The double-conversion or on-line topology is considered as the superior topology in performance, and is widely used as standard solution for protecting sensitive loads. However, it has lower efficiency as compared to other topologies due to two conversion stages in its structure. In other words, power flow through the rectifier and inverter even during the standby mode means higher power losses and lower efficiency compared to passive-standby and line-interactive UPS systems.

Another important feature of the online topology is the decoupling of the input from the output, which allows converting single-phase to three-phase UPS [5].

In view of the machine efficiency, power factor, and torque ripples, a three-phase induction motor is preferable to a single-phase induction motor. Therefore, it is desirable to replace the single-phase induction motor drives by the three phase induction motor drives .Even if the distribution of electric power is typically three phase, where only a single-phase utility is available, a single-phase-to-three-phase power converter system is required to feed the three-phase induction motor drives. In rural electric systems, the cost of bringing three-phase power to a remote location is often high due to high cost for a three-phase extension. Furthermore the rate structure of a three-phase service is higher than that for single-phase service. Therefore, single-phase to three-phase power converters are excellent choices for situations where three-phase power is not available. Sometimes, a specific appliance needs three-phase power, requiring some kind of power conversion [6]. Such converters have a wide range of applications in which a three-phase motor is a main component and the available supply is single-phase. This happens in residential, light industrial, farming, low-power industrial applications and rural areas [7], [8], and [9]. Fig.1 shows a typical 1-phase to 3-phase dual bridge converter topology.

The simplicity of these circuits inherently requires a simple control. However, they suffer from large number of switches and from here high cost. The problem of reduction the cost of converters has been recently attracting the attention of researchers [10]-[12].

Reducing the number of switches brings one of the most significant cost reductions. Another method of cost reduction is replacing active switches, such as MOSFETs, IGBTs and thyristors with diodes. Not only diodes are cheaper than active switches, but there is also cost reduction from eliminating gate drivers for active switches. Replacing active switches with diodes usually complicates circuit topology and reduces degrees of freedom in the control system. Therefore, the control is usually more sophisticated [5].

One way to increase the efficiency of the drive is by reducing its losses. These losses are computed as switching losses and conduction losses. It may also be improved as the number of circuit elements is minimized, because as the number of devices reduces the associated amount of switching reduces and so the losses are minimized. Also too many power switches at the same time reduces the reliability of the power conversion system [13].

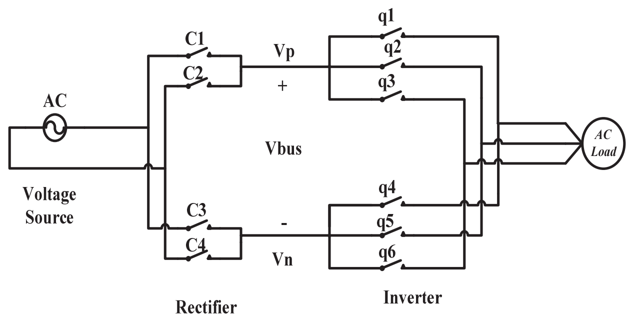

Fig. 1: A typical dual bridge single phase to three phase converter topology.

In this paper, after a brief presentation of several topologies, reduced number of switches is studied. The concept of reducing the cost of converters is applied by using four-switch three-phase DC/AC inverter instead of six switch three-phase DC/AC topology, but with similar functionality. In addition, the cost of the proposed UPS system is reduced further by employing a novel single-phase AC/DC rectifier topology with just one switch and four diodes. Also a balancing control of the neutral voltage in the dc link is applied for the symmetrical output voltage of the DC/AC converter. Finally, simulation results are provided to validate its operation.

II. Steps to Reduce the Switch Number

A. Reduced steps of the AC to AC converters

Considering the conventional AC to AC converter topology was shown in Fig. 1. In general, the ten ideal switches in Fig. 1 requiring, in principle, twenty unidirectional current conducting, bidirectional voltage blocking switches can be implemented in a number of simpler realizations by appropriate assumptions. For example, if Vp is always higher than Vn, the bidirectional switches on the load side can be replaced by uni-directional voltage blocking switches as shown in Fig. 2. In this case, the topology of [14], [15], and [16] is realized.

Fig. 3 shows the equivalent circuit of input side phase. Noting that the switches Spp and Snp can share the same gate drives signal. These two switches can be replaced by one single switch and two clamp diodes. As a result, a 12-switch topology is developed as shown in Fig. 4. [17], [18]. Compared to the 14-switch topology, this circuit possesses the same performance measures such as four-quadrant operation, unity power factor and low harmonic content. The first difference is that, when DC current, i_{dc}, is positive, its conduction losses for the line side switches are higher than the 14-switch topology.

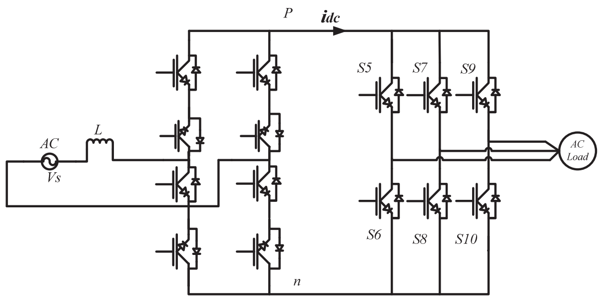

Fig. 2: Topology with 14 uni-directional voltage blocking switches.

If the condition that link current, $i_{dc} > 0$ is guaranteed, the number of switches can be further reduced. If the 12-switch topology in Fig. 4 is analyzed in detail, a 10-switch topology can be derived as presented in Fig. 5.

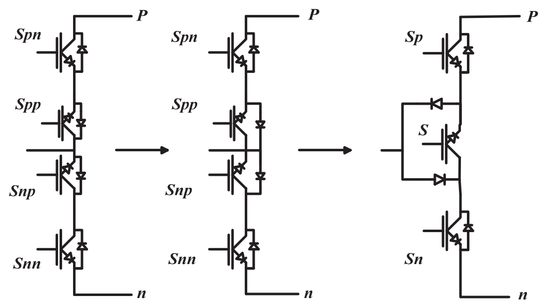

Fig. 3: Steps to reduce the switch number.

From Fig. 4, it can also be determined that no current flows through Sjp and Sjn, (j € a, b) and only the two intermediate switches are conducting. Thus, an 8-switch topology can be obtained as shown in Fig. 6. Generally, both the 8-switch and the 10-switch topologies show the same performance except that the 8-switch topology has somewhat larger conduction losses than the 10-switch topology.

Because an 8-switch topology can only be used when DC Current, i_{dc}, is greater than or equal to zero, the power through that, can only flow from the line side to the load side. In order to ensure positive DC current flow with three-phase sinusoidal output current, it can obtain that the power factor on the load side should always be higher than 0.87. As a result, the application of this topology is somewhat limited but suitable, for example, for permanent magnet motor drives [19].

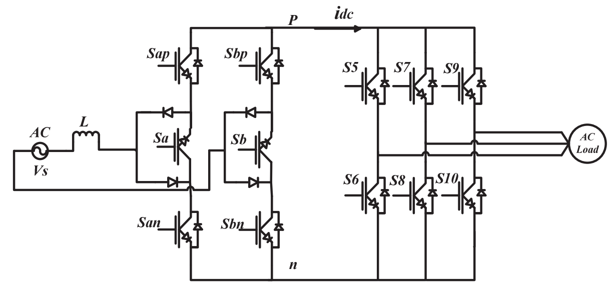

Fig. 4: A Reduction of switch number from 14 to 12.

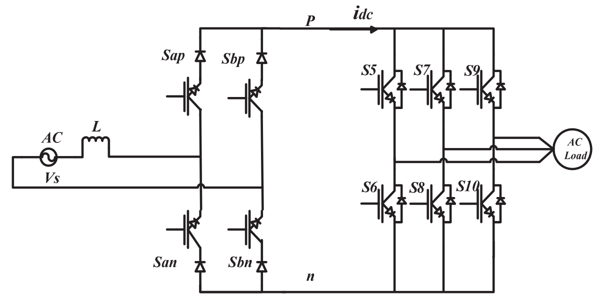

Fig. 5: 10-switch topology.

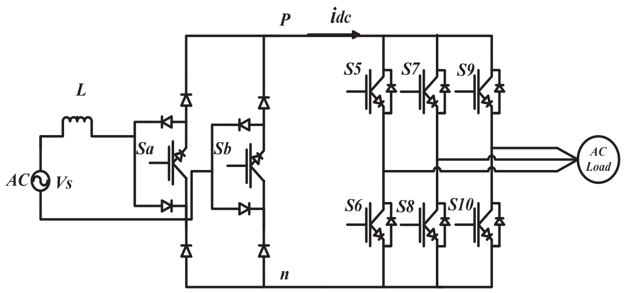

Fig. 6: 8-switch topology

B. Reduced steps of the single-phase to three phase UPS

Typical single-phase to three-phase on-line UPS topology is shown in Fig. 7. In circuit of Fig. 8, compared with the circuit of Fig. 7, the number of the converter's switches is reduced to 8, whereas it retains the function of the topology in Fig. 7. However, it also has some disadvantages such as higher output current distortion and doubly high dc-link voltage requirement [20].

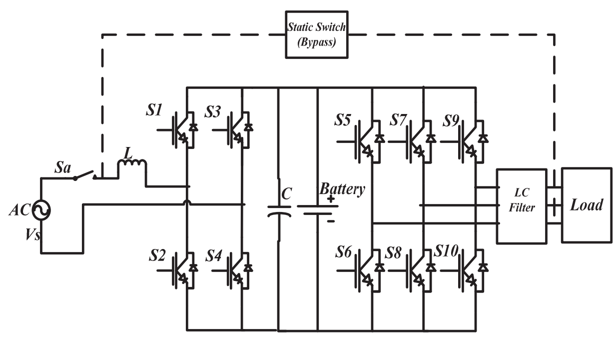

Fig. 7: A 10-switches typical single-phase to three-phase on-line UPS topology

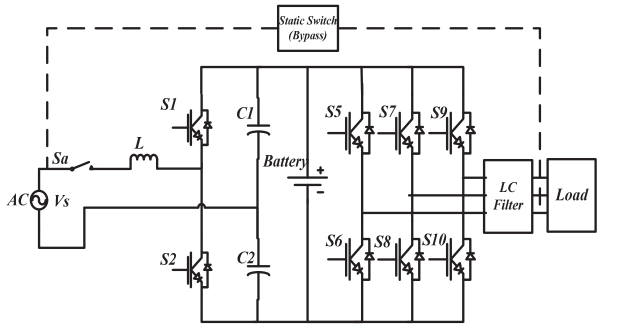

Fig. 8: 8-switches typical single-phase to three-phase on-line UPS topology

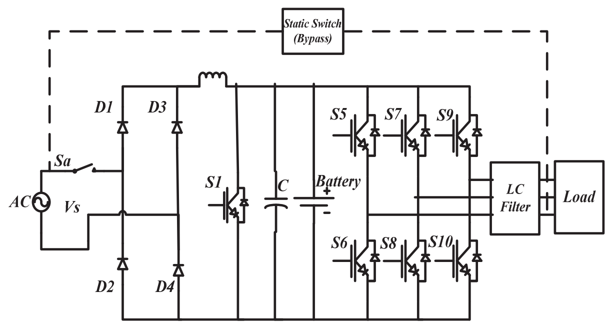

Fig. 9: 7-switches typical single-phase to three-phase on-line UPS topology

Also, in circuit of Fig. 9, the number of the converter's switches is reduced to 7. It has 4 rectifier diodes too. In fact, reduced switch count can be obtained by using capacitor midpoint connection [21] or sharing converter legs [22].

III. Proposed System

The proposed new UPS system is shown in Fig. 10. It consists of a rectifier, two battery sets and a two-leg inverter. The rectifier consists of four diodes D1, D2, D3, D4, one inductor *Lf*, one IGBT, and two electrolytic capacitors C1, C2.

The two battery sets are directly connected to the split capacitor dc bus resulting in a simple system. The three-phase inverter consists of four switches *S1*, *S2*, *S3* and *S4* [5]. Voltage conversion ratio in proposed topology is equal to previous topologies.

There are two operating modes related to this topology: normal mode and stored energy mode:

- *Normal Mode of Operation*

During this mode of operation, the power to the load is continuously supplied via the rectifier/charger and inverter. In fact, a double conversion, that is, AC/DC and DC/AC, takes place. It allows very good line conditioning .The AC/DC converter charges the battery set and supplies power to the load via the inverter. Therefore, it has the highest power rating in this topology, increasing the cost.

- *Stored-Energy Mode of Operation*

When the AC input voltage is outside the preset tolerance, the inverter and battery maintain continuity of power to the load. The duration of this mode is the duration of the preset UPS backup time or until the AC line returns within the preset tolerance. When the AC line returns, a phase-locked loop (PLL) makes the load voltage in phase with the input voltage and after that the UPS system returns to the normal operating mode.

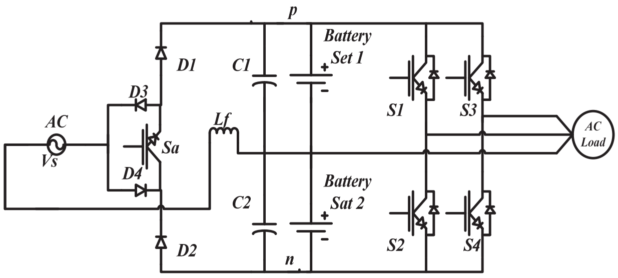

Fig. 10: The proposed new single-phase to three-phase on-line UPS topology

IV. Simulation Results

Time-domain simulations are carried out to verify the theoretical studies and evaluate the performance of the proposed topology. The simulations are performed using PSIM software. The simulated system parameters are given in Table I.

TABLE 1
System Parameters

Parameters	Rating
Power	1.2 kW
Input Voltage	220 VAC
Input Filter	L=100μH
Output Voltage (line-line)	300 VAC
Output Voltage THD	3.1 %
Load	L=10 mH , R= 40 Ω
DC-Link Voltage	650-700 VDC

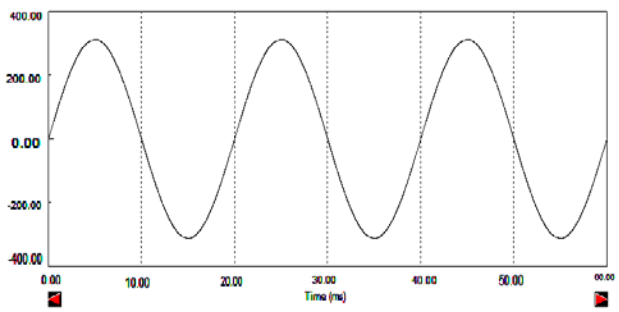

Fig. 11: Simulation results for the input voltage

Fig. 11 to 15 show the simulation results for the proposed system. Fig. 11 shows the input ac line voltage. Fig. 12 shows the simulation results for DC link voltage of proposed system. Fig. 13 and 14 show the simulation results for output current and output voltage, respectively. Also, Fig. 15 shows the frequency domain of output voltage. It can be found that the output voltage is regulated sinusoidal waveform.

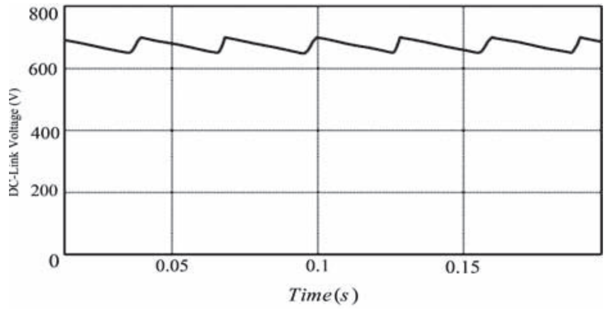

Fig. 12: Simulation results for DC link voltage

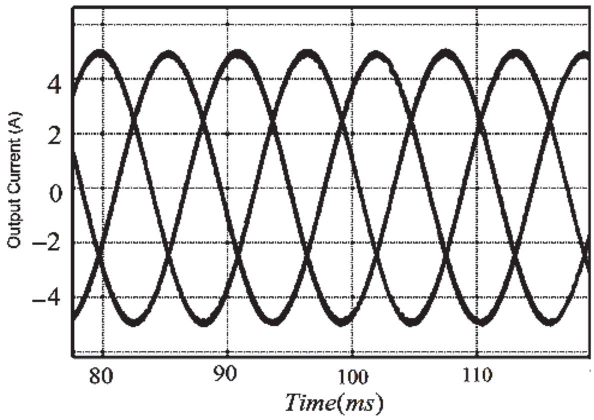

Fig. 13: Simulation results for output current

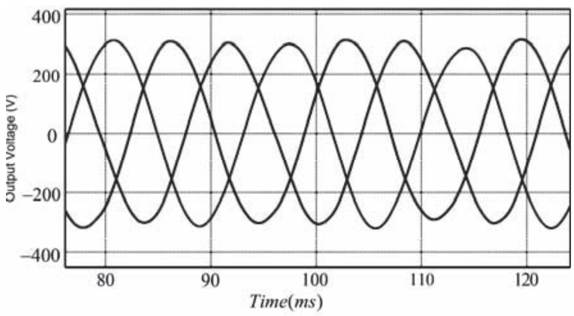

Fig. 14: Simulation results for three-phase phase to neutral output voltage.

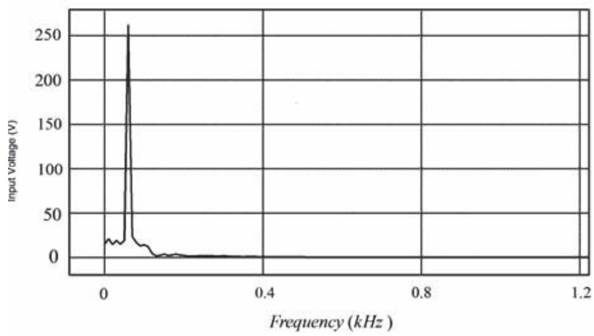

Fig. 15: Simulation results for output voltage frequency domain

V. Conclusion

This paper investigates the performance of a new reduced switch online single-phase to three-phase UPS topology. It is based on a single phase AC/DC rectifier converter and a three-phase two leg DC/AC inverter. It is suitable for sensitive loads because it guarantees the three-phase power quality that means: sinusoidal, balanced, and symmetrical voltages even with nonlinear and unbalanced loads. The topology has only 5 switches. The concept of cost reduction for the converters is applied by reducing the number of switches. The reduced number of switches results in lower cost, greater compactness, and higher reliability than those of the conventional counterparts. The circuit topology, operation, and control strategy have been described and as simulation results are also presented to verify its feasibility.

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BIOGRAPHIES

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