Modern Transformerless Uninterruptable Power Supply (UPS) Systems

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Abstract

Uninterruptable power supplies (UPS) are widely used to supply critical loads and provide reliable and high quality energy to the load. Until recently, on-line UPS systems with isolation transformer have been widely employed. However, transformerless modern UPS systems have been rapidly replacing the old technology due to their superior performance and size attributes. Transformerless UPS systems have utility friendly input performance and high quality output voltage waveform. Furthermore, smaller size, higher efficiency, and increased reliability are features that spread the transformerless products, rendering the transformer technology obsolete. In this paper, modern transformerless UPS systems with the 6-300kVA range will be discussed and their experimental performance will be illustrated. Input and output power quality performances, energy efficiency performance, and size/weight information will be provided on modern commercial transformerless UPS products.

1. Introduction

Uninterruptable power supply (UPS) systems are employed to supply the critical loads with continuous and high quality energy in facilities such as hospitals, data centers, and communication systems etc. There are three primary types of static UPS: on-line, off-line, and line-interactive, which all differ in their ability to perform these critical functions and vary in the degree of security and level of power protection they provide. Line-interactive and off-line UPS systems are limited in their design to smaller applications such as home and small office. By comparison, on-line UPS systems provide superior electrical performance, reliability, and resilience. Therefore, majority of industrial (factories), infrastructural (hospitals, security centers), financial (banks), etc. systems with several kVA and higher ratings employ on-line UPS systems [1]. A UPS incorporates a rectifier which converts the AC mains voltage to DC voltage and an inverter, which via discrete voltage pulses creates an AC waveform from the DC supply (from the rectifier output) and after an LC filtering stage provides the output to power the connected load. In an on-line UPS, the rectifier and the inverter are designed for continuous operation. Its inverter operation is unaffected by changes in the voltage or frequency supplied by the mains power. To provide energy source to the constantly running inverter of an on-line UPS, the mains connected rectifier is a very important subcircuit of the UPS and its performance is essential both to the UPS and to the mains. Particularly, in transformerless UPS systems, the rectifier performance exhibits a major difference from the conventional (or more appropriately, the old) technology UPSs with isolation transformer [2], [3].

Rectifiers can generate high level of harmonics and may draw reactive power, depending upon their design, method of operation, and type of UPS they are employed in. In a transformer based three-phase UPS, the rectifier side consists of a thyristor rectifier bridge, which can be of 6-pulse or 12-pulse type. The rectifier thyristors are fired to obtain constant DC bus voltage (nearly 400 V). The thyristor rectifier creates significant amount of low frequency characteristic harmonics (5^{th}, 7^{th}, 11^{th}, 13^{th}, etc.) because of its low frequency commutation nature, so large size low frequency input harmonic filters are needed to reduce the input current harmonics. These harmonic filters have negative effect on the overall system efficiency. Furthermore, the reactive power demand of the thyristor rectifier should be compensated by means of capacitive filters that increase the size and cost and decrease the reliability and increase the harmonic resonance risk with the power line [2]-[4].

The inverter side of transformer based UPS contains a boost transformer to create AC voltage waveform compatible with the original (nominal) input voltage. In a three-phase UPS, when the DC bus voltage is 400 V, the inverter cannot generate 220 V_{rms}/phase voltage without the boost transformer. Since the transformer transfers power at the rated output frequency of 50 Hz, it is heavy and bulky, which leads to significant weight and volume increase of the transformer based UPS. The transformer is also a heat source, which leads to significant overall system efficiency degradation. Furthermore, the thermal design becomes complex and the thermal reliability degrades significantly. In particular for the relatively high power transformer based UPS systems involving 12-pulse input rectifiers with phase shift transformers, the size, weight, and complexity is further exacerbated that leads to unfavorable performance, cost, and reliability [2], [3].The modern technology transformerless UPS systems do not contain output stage isolation transformers or input stage phase-shift transformers. Advances in power semiconductor technology and microprocessor technology have enabled the use of Insulated Gate Bipolar Transistor (IGBT) switches in forced commutated PWM boost rectifiers [5] instead of the thyristors in the conventional phase controlled rectifiers at the input stage of on-line UPSs. The IGBTs are employed in the PWM rectifier can boost the intermediate DC bus voltage to much higher level than the phase controlled rectifier (approximately 800V) than the transformer based UPS case. This allows the inverter to directly produce an AC output voltage compatible with original (rated) input voltage. The transformer is removed, and all of its side effects (efficiency degradation, size/weight increase, thermal reliability degradation, etc.) disappear along with it.

Furthermore, the transformerless UPS systems provide significantly better input power factor (near unity PF with flat characteristic) and current total harmonic distortion than the UPS with isolation transformer (THD_i<5% with flat characteristic). Allowing regenerative mode of operation, providing good dynamic response, and providing high output voltage quality under high crest factor and/or unbalanced load conditions. Improved battery management also becomes possible with the improved rectifier operation.

The overall advantages of modern transformerless UPS systems over those with isolation transformer (which are now considered obsolete) can be summed up and summarized as input-output power quality enhancement, lower operating and energy cost with high return on investment on the new technology UPS, and significantly enhanced reliability. The new technology transformerless UPS systems are currently under heavy R&D investigation around the world and their evolution continues. This paper summarizes the transformerless UPS technology pointing out the salient performance features of such devices. The recently developed commercial products with a wide power range (3-300kVA) are considered [6] and the experimental performance of such devices is reported.

The paper first reviews the transformerless UPS topologies and then continues with the input and output performance evaluation of commercial products. Finally performance evaluation, comparison with conventional systems and conclusions is provided.

2. Transformerless UPS Topologies

In Fig. 1, a single-phase modern transformerless UPS circuit diagram is shown. The single-phase UPS has a voltage boost power factor correction (PFC) circuit at the input stage in order to maintain the required DC bus voltage (800 V) and obtain high input power quality (unity power factor and low current THD). Due to its boost topology structure, the PFC circuit can produce high DC voltage levels, so that inverter unit can produce AC output without a need of step-up (boost) transformer at the output stage. A two-level (Fig. 2.a) or preferably three-level inverter topology (Fig. 2.b or as in Fig. 1 output stage) may be used in the output inverter stage of the UPS [7], [8]. By using the three-level topology, the overall efficiency of the inverter can be made higher than the two-level inverter based UPS. Also the output filter size of the inverter can be designed smaller.

In Fig. 3, a three-phase modern transformerless UPS circuit diagram is shown. The rectifier part of the UPS consists of a Voltage Source Converter (VSC) [5], which is also called as PWM boost rectifier. The VSC can provide constant output DC bus voltage, low total harmonic distortion (THD) in the mains currents, bidirectional power flow, and a fully controllable power factor [5]. The half bridge inverter topology is used in the inverter unit of the three-phase UPS. There also exist other inverter topologies such as the four-leg inverter [9]. With the use of four-leg inverter topology, there is no need for a common neutral point in the DC busbar. However in half bridge inverters all three output phases can be controlled independently. Also due to the cost of the additional inverter leg, commonly the half bridge topology is used.

If the UPS fails, the load is bypassed to raw mains by means of the static-switch by-pass circuit made of back to back thyristors. This arrangement is equally true for transformer or transformerless design, with the difference being in the implementation of the rectifier, inverter, and battery circuits. The by-pass circuit also allows the UPS to operate with high energy efficiency during the non-critical load operating hours in a facility. The so called eco-mod operation is favorable in many applications that it also finds very wide use in the application. Thus, even the isolation transformer based UPS uses such a configuration, rendering the galvanic isolation property of the UPS. As a result it can be stated that both UPS configurations are without true galvanic isolation property (which is only demanded by very few special applications).

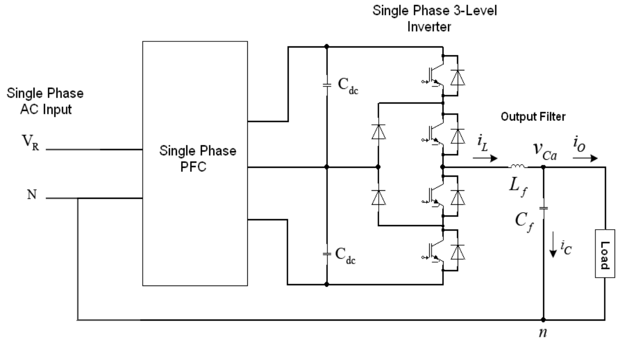


Fig. 1. The single-phase modern transformerless UPS circuit (employing a three-level inverter output stage) diagram

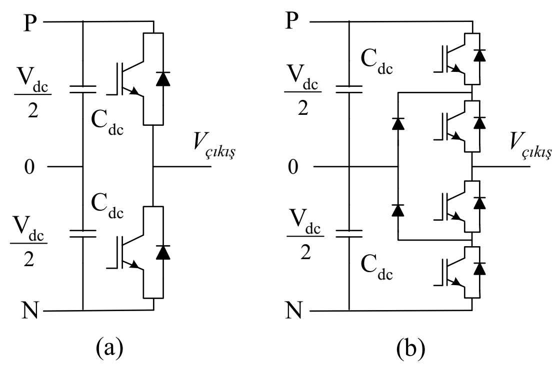


Fig. 2. (a) Two-level voltage source inverter topology, (b) three-level inverter circuit topology diagram

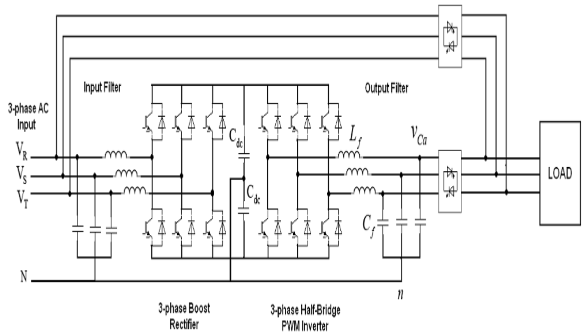


Fig. 3. Three-phase transformerless UPS circuit diagram

In particular in the three-phase transformerless UPS systems with high power ratings, the energy efficiency becomes an issue. There, the three-level inverter topology becomes attractive at both the input and output stages of the transformerless UPS system. In the two-level inverter, the phase to neutral output voltage is composed of switching voltages of $V_{dc}/2$ and $-V_{dc}/2$. So the stress on the filtering elements are higher, large output filter is needed. Besides, the switching losses of the IGBT's are high due to the switching of total DC bus voltage. However, for the three-level inverter case, the phase to neutral output voltage is composed of switching voltages of $V_{dc}/2$, 0 and $-V_{dc}/2$. The stress on the output filter elements and the IGBT losses is smaller. So the overall efficiency of the three-level inverter is higher than the two-level inverter. Thus, the transformerless UPS technology is evolving in this direction and products of this topology type are becoming more and more common.

3. Transformerless UPS Experimental Performance Evaluation and Comparisons

In this section the laboratory test results and waveforms of the recently developed commercial modern transformerless UPS' are shown. In the first step, single-phase input and single-phase output transformerless UPS test results are shown. Then three-phase input and three-phase output transformerless UPS waveforms and experimental results are shown. Mainly, input and output power quality performances and energy efficiency are considered. Due to the space limitation, only the prime characteristics are shown while other performance results can be obtained from the product datasheets [6] and other literature [3].

3.1. Single Phase UPS Experimental Results

In the following, single-phase modern transformerless UPS performance is demonstrated. The power rating of the UPS product, of which the photograph is shown in Fig. 4, is 6kVA. The dimensions and weight of this UPS are 255×630×550mm (W×D×H) and 28kg (without battery), approximately half size of that with the transformer. The input circuit part of the UPS contains power factor correction (PFC) circuit to boost the DC voltage and reduce input current THD. The inverter topology of the UPS is three-level inverter topology shown in Fig. 1 and Fig. 2 in detail. As shown in Fig. 5, the input current waveform is sinusoidal and has low harmonic content. The input current is utility grid friendly and the power factor is nearly unity. The harmonic spectrum of the input current is shown in Fig. 6. The input current THD is below 5%.

As mentioned above, the inverter topology of the UPS is three-level inverter topology. Three-level inverter topology has been employed in low voltage ratings in recent applications. One of the major advantages of the three-level inverter topology is the high inverter performance under nonlinear loads. The three-level inverter superior performance is shown in Fig. 7. The output voltage waveform is sinusoidal as shown in Fig. 7. The load current crest factor (CF_i) is 3.4. This value is quite high for a nonlinear load. The harmonic content of the waveform is below 4% as seen from Fig. 8. A further advantage of this topology regards the energy efficiency. Fig. 9 shows that this UPS provides high energy efficiency over a wide load range by exhibiting a flat curve. The energy savings this UPS provides allows the UPS to pay back the investment cost within only several months [3].

Fig. 4. A 6 kVA rated single-phase modern transformerless UPS [6]

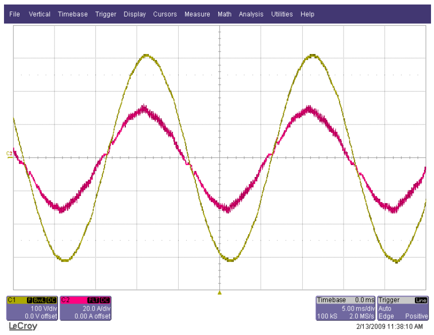


Fig. 5. Input voltage and current waveforms of the 6kVA single-phase UPS at 100% load (C1: 100V/div, C2: 20A/div, and time: 5ms/div)

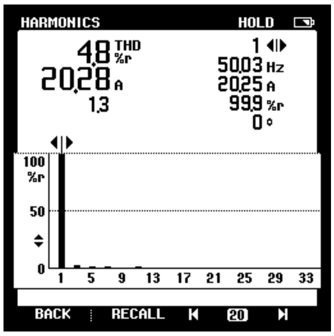


Fig. 6. Input current harmonic spectrum of the 6kVA single-phase UPS at 100% load

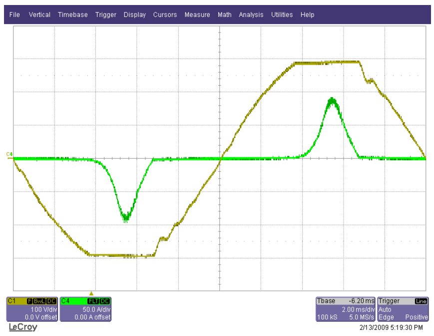


Fig. 7. Output voltage and current (CF=3.4) waveforms of the 6kVA single-phase UPS at 100% nonlinear load (C1: 100V/div, C2: 20A/div, and time: 5ms/div)

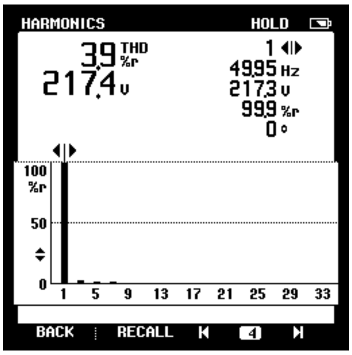


Fig. 8. Output voltage harmonic spectrum of the 6kVA single-phase UPS at 100% nonlinear load (CF_i=3.4)

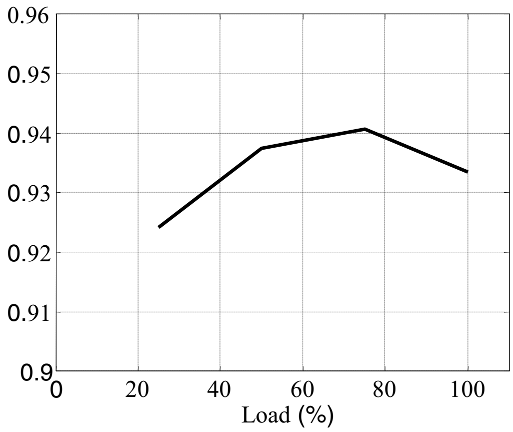


Fig. 9. The energy efficiency curve of the 6kVA single-phase UPS under linear resistive load

3.2. Three Phase UPS Experimental Results

In the following, three-phase input and three-phase output modern transformerless UPS experimental performance is demonstrated. The output power rating of the UPS product, of which the photograph is shown in Fig. 10, is 60 kVA with the output power factor of 0.8. The dimensions and weight of this UPS are 530×860×1450mm (W×D×H) and 282kg (without battery), approximately half size of that with the transformer. The circuit topology of this UPS is the same as shown in Fig. 3 which employs two-level half-bridge inverters both at the input and output stages. The PWM boost rectifier uses IGBT's and boosts the DC bus voltage to 800 V. Via vector controlled PWM mode operation it provides high quality input currents. In the Fig.11, the input current and voltage waveforms at full load are shown. The input current waveform is sinusoidal and has low harmonic content. The input current does not distort the input voltage and the input power factor is near unity. The harmonic table of the input current waveform is shown in Fig. 12. The line current THD_i is less than 4%. Also the input is harmonic resonance risk free, reliable system.

In Fig. 13, the output voltage and the load current waveforms are shown. The load current waveform is nonlinear and has crest factor of 3.4. The output voltage waveform has sinusoidal form and its rms value is maintained at $220V_{rms}$. The harmonic table of the output voltage waveform is shown in Fig.14. The output voltage THD under this highly distorted loading condition is maintained below 4%. Hence, high output performance.

Ranging from 15kVA to 300kVA, these transformerless UPS systems provide high energy efficiency (at rated load from 88% to 94%, about 2% better than transformer based systems [3]). With the three-level inverter technology applied to such systems, higher efficiency range is obtainable. Such products have been prototyped and are currently under development. Although the initial cost of such systems is slightly higher than the two-level structures, the increasing energy cost makes the return on the three-level UPS systems investment very rapid (additional cost is recovered within only a few months). Thus, the newer technologies are favorable.

Fig. 10. A 60 kVA rated three-phase modern transformerless UPS [6]

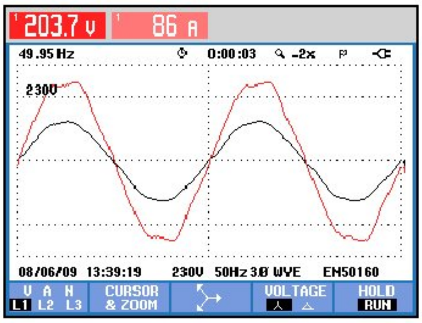
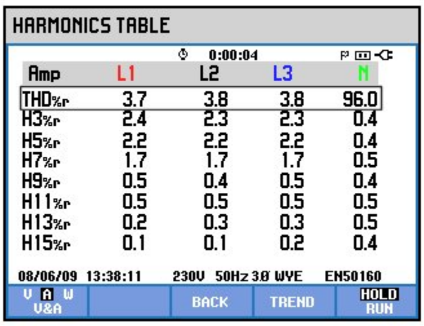


Fig. 11. Input voltage and current waveforms of the 60 kVA three-phase transformerless UPS at 100% load



HARMONICS TABLE

Amp	L1	L2	L3	N
THD%r	3.7	3.8	3.8	96.0
H3%r	2.4	2.3	2.3	0.4
H5%r	2.2	2.2	2.2	0.4
H7%r	1.7	1.7	1.7	0.5
H9%r	0.5	0.4	0.5	0.4
H11%r	0.5	0.5	0.5	0.5
H13%r	0.2	0.3	0.3	0.5
H15%r	0.1	0.1	0.2	0.4

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Fig. 12. Input current harmonic table of the 60 kVA three-phase transformerless UPS at 100% load

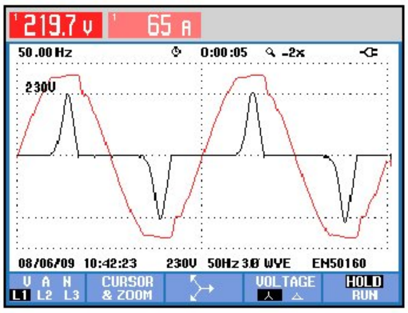

Fig. 13. Output voltage and current (CF_i=3.4) waveforms of the 60 kVA three-phase UPS at 100% nonlinear load

HARMONICS TABLE

0:00:06

Volt	L1	L2	L3	N
THD%r	3.9	3.9	3.9	90.7
H3%r	1.6	1.5	1.3	65.9
H5%r	1.4	1.3	1.5	8.1
H7%r	2.2	2.1	2.1	5.5
H9%r	1.1	1.2	1.3	45.5
H11%r	0.6	0.6	0.7	5.9
H13%r	0.8	0.8	0.7	2.3
H15%r	0.9	0.9	0.9	28.4

08/06/09 10:42:38 230V 50Hz 3Ø WYE EN50160

V A W V&A | BACK | TREND | HOLD RUN

Fig. 14. Output voltage harmonic table of the 60 kVA three-phase transformerless UPS at 100% nonlinear load (CF_i=3.4)

In Fig. 14, photograph of a 40kVA power rated three-phase modern transformerless UPS is shown. The dimensions and weight of this UPS are 480×1075×900mm (W×D×H) and 190kg (without battery). The THD_i of this UPS is also lower than 4% and the efficiency is near %92. This unit has internal battery racks and compact structure. It is an economical solution wherever uninterruptable energy is required.

Fig. 15. A 40 kVA rated three-phase modern transformerless UPS with compact mechanical design [6]

4. Conclusion

Transformerless modern UPS systems have been rapidly replacing the old technology due to their superior performance and size attributes. Transformerless UPS systems have utility friendly input performance and high quality output voltage waveform. Furthermore, smaller size, higher efficiency, and increased reliability are features that spread the transformerless products, rendering the transformer technology obsolete. In this paper, via recently developed modern transformerless UPS systems (with the wide power range 6-300kVA shown in Fig. 15) the performance of such systems has been experimentally demonstrated. With UPS line side power factor being near unity and line current THD being less than 5% over a wide load range, the input power quality is superb. The output voltage quality is very high even under highly distorted crest factor load. The output voltage regulation is within 1% and harmonic distortion is less than 4%. Therefore, it is expected that the transformerless UPS systems to render the transformer based UPS systems obsolete, not only in new installations but also in retrofit applications along with the replacement of the older systems with the energy efficient new systems.

Fig. 15. 6-300kVA rated transformerless UPS family [6]

5. References

[1] A. King and W. Knight, *Uninterruptible power supplies and standby power systems*, McGraw-Hill, 1. Ed., 2003.

[2] R. Koffler, “Transformer or transformerless UPS?” IEE Power Eng. Journal, Vol. 17, no. 3, pp. 34-36, 2003.

[3] A.M. Hava, “Enhancing the power quality, energy efficiency, and environmental cleanness with transformerless UPS systems,” EVK 2009 Conference, May 2009, Kocaeli, Turkey, pp. 154-158.

[4] R.C. Dugan, M.F. McGranaghan, S. Santoso, H.W. Beaty, *Electrical power systems quality,* McGraw-Hill, 2. Edition, 2002.

[5] V. Kaura, V. Blasko, “Operation of a Voltage Source Converter at Increased Utility Voltage,” IEEE Trans. On Power Electronics, Vol.12, No.1, January 1981.

[6] http://www.enel.com.tr (latest accessed date: 12/06/2009).

[7] A. Nabae, I. Takahashi, H. Akagi, “A new neutral-point-clamped PWM inverter,” IEEE Trans. Ind. Appl., Vol.17, No.5, pp.518-523, 1981.

[8] R. Teichmann and S. Bernet, **“**A comparison of three-level converters versus two-level converters for low-voltage drives, traction, and utility applications,” IEEE Trans. Ind. Appl., Vol.41, No.3, pp. 855-865, 2005.

[9] E. Demirkutlu and A.M. Hava, “A Scalar Resonant Filter Bank Based Output Voltage Control Method and a Scalar Minimum Switching Loss Discontinuous PWM Method for the Four-leg Inverter Based Three-phase Four-wire Power Supply,” IEEE Trans. Ind. Appl., Vol. IA-45, No. 3, pp. 982-991, May/June 2009.

[10] Y. Dote and R.G. Hoft, *Intelligent Control: Power Electronic Systems,* Oxford University Press, 1998.