Renewable and Sustainable Energy Reviews 58 (2016) 1395–1410

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Review: Uninterruptible Power Supply (UPS) system

Muhammad Aamir, Kafeel Ahmed Kalwar, Saad Mekhilef*

Power Electronics and Renewable Energy Research Laboratory (PEARL), Department of Electrical Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia

ARTICLE INFO

Article history:
Received 2 August 2014
Received in revised form
7 September 2015
Accepted 18 December 2015
Available online 18 January 2016

Keywords:
Uninterruptible Power Supply (UPS)
Energy Storage
Control Methods
Topologies

ABSTRACT

Uninterruptible Power Supplies (UPS) have reached a mature level by providing clean and uninterruptible power to the sensitive loads in all grid conditions. Generally UPS system provides regulated sinusoidal output voltage, with low total harmonics distortion (THD), and high input power factor irrespective of the changes in the grid voltage. This paper provides comprehensive review of UPS topologies, circuit configurations, and different control techniques used in the UPS system. A comparison based on the performance, size, cost, and efficiency of the system is presented. Different hybrid energy source UPS system and new generation UPS system for smart grid and micro-grid has been explained. Finally the paper describes performance evaluation of UPS system and explains different aspects that are to be considered for choosing a suitable UPS system by the user.

Contents

* Corresponding author. Tel.: +60 379676851.
E-mail address: saad@um.edu.my (S. Mekhilef).

http://dx.doi.org/10.1016/j.rser.2015.12.335
1364-0321/

1. Introduction

Uninterruptible power supply (UPS) system provides clean, conditioned, and uninterruptible power to the sensitive loads such as airlines computers, data centres, communication systems, and medicals support systems in hospitals etc. Generally the output of the UPS system must be regulated sinusoidal with low total harmonic distortion (THD), irrespective of the changes in the input voltage and abrupt changes in the load connected to the system [1]. Besides, low transients response time from online mode to battery powered mode and vice versa, unity power factor, high reliability, high efficiency, low cost, low weight, and small size, etc. are other essential considerations in the UPS system.

Broadly the UPS can be classified as the Static UPS system and Rotary UPS system. The static UPS system uses power electronics converters and inverters to process, store, and deliver power in grid failure, while Rotary UPS uses motors and generators for the same function. Sometime the combination of both static and rotary UPS system is used usually called hybrid UPS System [2,3]. Wide range of UPS systems is available in the market depending upon their ratings. The smaller units of only 300VA are used to provide back up to single computer, but the bigger unit of UPS may provide backup to entire building of several megawatts.

To cope with the recent issues of global warming and greenhouse gas emission, the use of renewable energy resources is tremendously increasing. UPS system with photovoltaic power has also been introduced in [4,5] to utilize the solar energy for longer period of time.

Commercially all the UPS system must fulfil the following requirements in order to maintain the output voltage [6,7].

1. Constant steady state RMS voltage for 2% variation in any parameter like temperature, load current, or battery voltage.
2. Maximum of 10% transient peak voltage deviation is allowed during both loading and unloading of the UPS system.
3. Voltage drop of not more than 5% of the rated voltage cannot be tolerated for more than 2 AC cycles.
4. Inverter output voltage with total Harmonic distortion (THD) of only 4% is allowed for all the load conditions.

This paper describes the classification of UPS system, different line faults, and the recommended UPS system for these faults. Also the state of the art high efficiency, low cost, and small size systems are covered and classified based on the circuit structure. Furthermore a comparison of a transformer based and transformer-less is described based on which a recommendation of a particular topology has been given depending upon the required power ratings.

2. Classification of UPS

Depending on the topological configuration, the UPS system is classified as Offline UPS, Line interactive UPS, and Online UPS system [8–12].

2.1. *Offline UPS*

The offline UPS consists of a battery charger, a static switch, and an inverter as shown in Fig. 1. A filter and a surge suppressor are sometimes used at the output of the UPS to avoid line noise and disturbance before being supplied at the output of the UPS. During normal mode operation, a battery charger will charge the battery bank, and at the same time the load is being fed by the power from main AC line. The inverter is at the standby during this mode. When there is a power failure, the static switch connects the load to the inverter and the power is fed by the battery through the

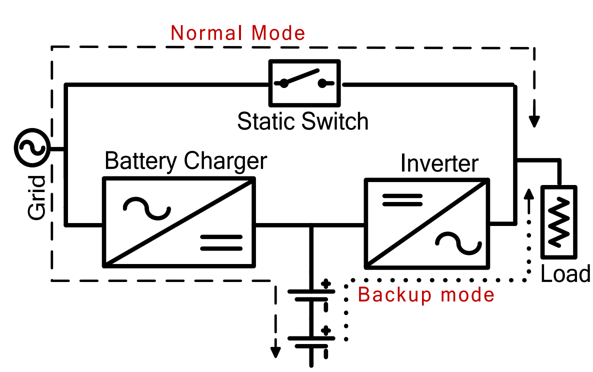

Fig. 1. Block Diagram of Offline UPS System.

inverter. The switching time of the static switch is normally less than 10ms, which does not affect the normal computer load. The advantages of the offline UPS are low cost, simple design, and smaller size of the system. But the lack of real isolation from the load and the lack of voltage regulation are the main drawbacks of the offline UPS system. Also the performance of this system during non-linear load is also very poor. Offline UPS are suitable for smaller loads with rating of about 600 VA.

2.2. Line Interactive UPS system

Line Interactive UPS consists of a static switch, bidirectional converter/inverter, and a battery bank as shown in Fig. 2. The bidirectional converter/inverter connects the battery bank to the load. During normal mode of operation, the main AC line supplies the power to the load and the bidirectional converter/inverter charges the battery. During the grid failure, the static switch disconnects the load from the main supply and the bidirectional converter/inverter supplies the power to the load. The line interactive UPS has the advantages of low cost, small size, and high efficiency. The only limitation is that it does not provide any voltage regulation during normal mode of operation. Generally the Line interactive UPS system is rated between 0.5 kVA and 5 kVA, and the efficiency of the system is normally greater than 97%, provided the main AC line is clean from any transients and spikes.

2.3. Online UPS System

Online UPS consist of a rectifier, an inverter, and a static switch as shown in the Fig. 3. During normal mode of operation, the rectifier charges the batteries as well as maintains the constant DC link voltage. While the inverter converts the DC link voltage to the required AC in order to feed the load. During power failure, the Magnetic Contactor (MC) disconnects the AC line, but the inverter keeps supplying power to the load from the battery bank without any interruption. Thus the inverter keeps on operation in both the modes. The inverter supplies clean, and conditioned power to the load irrespective of the harmonics and variations in the grid voltage. The advantages of the online UPS include isolation of the load from the main line and almost negligible switching time. The major drawbacks of the online UPS are low efficiency, low power factor, and high total harmonic distortion (THD). All the commercial units of 5 KVA and above are commonly online UPS system.

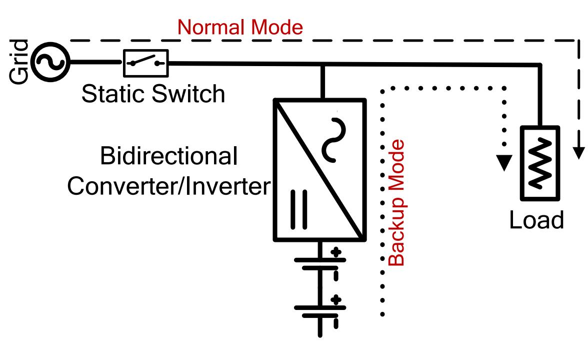

Fig. 2. Block Diagram of Line Interactive UPS system.

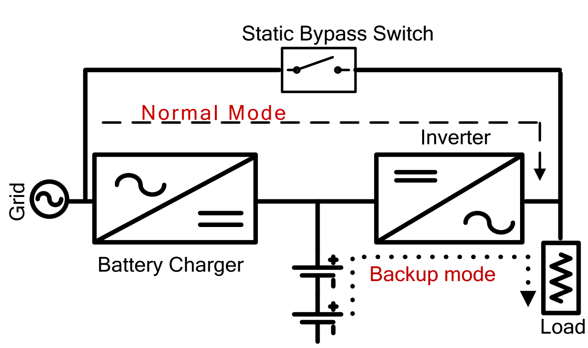

Fig. 3. Block Diagram of Online UPS system.

2.4. Power problems and UPS solutions

The power supplied by the grid is not always very clean and continuous. There may be some major faults in the system which leads to long interruptions and complete black out of the grid. Besides voltage swells and dropouts, voltage sag, harmonic distortion, etc. are other faults which are commonly encountered in the grid. Different UPS system provides protection against the specific faults as shown in the Table 1.

3. Topology-Based Classification

UPS system can be classified on the basis of the topologies and circuit configuration. The UPS system may be transformer-based, transformer-less, or high frequency transformer based. These UPS system are developed in the variety of configurations in order to fulfil the exact requirement of the application.

3.1. Conventional Transformer based UPS system

Fig. 4 shows the circuit diagram of conventional UPS system [13,14]. It consists of a rectifier, an inverter, line frequency transformers, and a bypass circuit. The rectifier converts the AC line voltage into DC link voltage in order to charge the battery bank and maintain a constant DC link voltage. The inverter converts the DC link voltage into the AC line voltage and provides the regulated sinusoidal voltage to the connected load. Two power frequency transformers are employed, one at the input side to step down the line voltage into low voltage of battery bank and the other at the output to step up the battery bank voltage as well as the operation

Table 1
Grid Disturbance and UPS Classification.

Sr. No	UPS System	Time	Common line Faults
1	Off-line UPS	> 10 ms	Line failure or long interruption, Voltage sags or dips, dynamic overvoltage
2	Line Interactive UPS	Continuous	Under voltage, Over voltage and voltage swell
3	Online UPS System	< 4 ms, Continuous and periodic	Transients, Harmonic distortion, Noise, frequency variations, Impulses

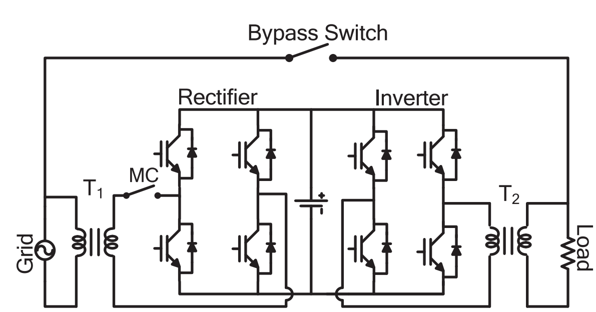

Fig. 4. Conventional UPS System.

of bypass switch [15]. Such system has an advantage of providing galvanic isolation from the transients and spikes generated inside the line grid. Also they are more robust in operation and can be designed for high power applications. But since both the transformers are operated at line frequency, so the size and weight of the system is enormously increased and so is the cost of the system. Also most of the switches are connected to the low voltage battery bank. So high current is flowing through these switches; causing extra current stress in these switches. Hence the efficiency of such systems is very low.

3.1.1. Single stage UPS system with trapezoidal AC supply [16]

Fig. 5 shows a single stage UPS system which generates a trapezoidal shape output voltage is specifically design for the optical fiber/coax cable hybrid networks. The circuit design of this UPS is almost similar to the conventional UPS system with the only difference of not using the power factor correction (PFC) circuit and smaller DC link capacitor used in the circuit. The trapezoidal shaped output voltage is synchronized with the input AC supply; hence smaller DC link capacitor is used to remove the current harmonics generated by the inverter. Since the line frequency transformer used in the system are more costly, and have high size and weight. Also the power factor of the system is considerable low because of the absence of the power factor correction circuit, thus this UPS system is not suitable for high power applications.

3.1.2. Three leg type converter

UPS systems using three leg type converter also gain much popularity due to reduced number of active switches [17–19]. Fig.6 shows the circuit diagram of the UPS system proposed in [17]. In three leg type converter, the first leg and the common leg act as rectifier which also charges the battery bank. The third leg and the common leg act as an inverter. The switches of the common leg are controlled at the line frequency. By using this common leg, the number of switches is reduced, which increases the overall efficiency of the system. Two leakage frequency transformers are used both at the input and output of the converter to reduce the cost of the system. Though the number of switches are reduces but two low frequency transformer increase the size and weight of the system. Also the batteries connected to the DC bus are high in number; charging and discharging at the same time. Thus continuous overcharging may reduce the battery life.

3.2. High Frequency Transformer Isolation

With the development in the semiconductor industry, fast switches and diodes are now available in the market with nearly ideal characteristics. Now the transformer can be used at high frequency with the advantages of reduced volume, inherent property of galvanic isolation, and improved efficiency of the system. Several UPS topologies with high frequency transformer have been introduced in [20–27]. Such UPS system has smaller size and weight as compare to the conventional UPS systems. But since high number of active switches is employed in such systems to operate the transformer at high frequency, it reduces the overall efficiency and increase the cost of the system.

3.2.1. A UPS with 110-V/220-V Input Voltage and High-frequency Transformer Isolation

Fig. 7 shows a flexible UPS topology which can operate over a wide range of input voltage [20]. During normal mode of operation, the chopper converts the grid voltage into DC and delivers high frequency pulses to the primary of the high frequency transformer. The transformer steps down the rectified voltage in order to charge the batteries. During the power failure mode, the battery bank voltage is stepped up using boost converter and is applied to the inverter which can supply regulated output voltage. Although this topology has the advantages of small size and weight because of the high frequency transformer and can also provide galvanic isolation. But high number of active switches and extra power processing stage decrease the efficiency of the system and add complexity to the circuit.

3.2.2. UPS System with BIFRED Converter

An improved UPS system using High frequency transformer is proposed in [21] as shown in the Fig. 8. In this topology, boost integrated flyback rectifier/energy storage DC–DC converter (BIFRED) has been used, which maintains the constant DC link voltage in order to feed it to the inverter and conventional

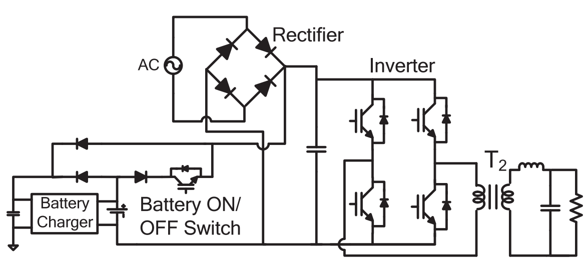

Fig. 5. Circuit diagram of Single Phase UPS system with trapezoidal AC Supply.

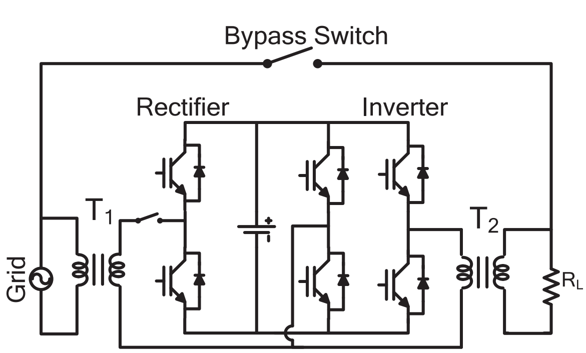

Fig. 6. Three Leg type converter proposed in [14].

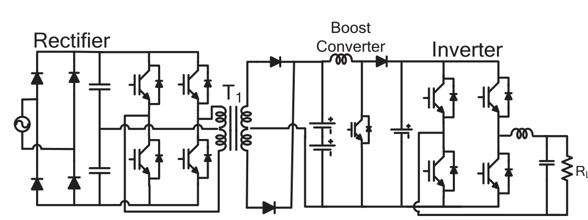

Fig. 7. UPS system proposed in [18].

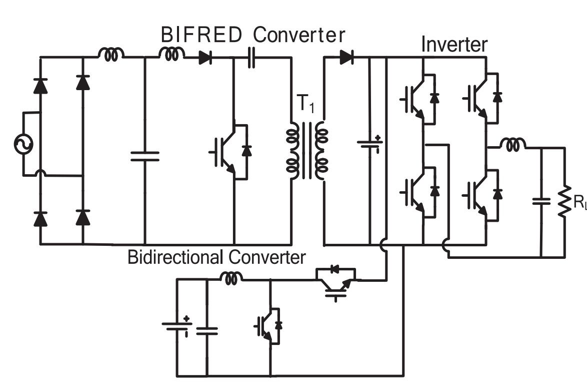

Fig. 8. UPS system with BIFRED Converter.

bidirectional converter is used to charge and discharge the battery. The circuit provides excellent power factor correction, and with high frequency transformer the size of the system is reduced considerable. But the battery bank voltage of the circuit will be increased significantly if the system is design for 220 V grid voltage.

3.2.3. Two stage UPS with high power factor correction

A two stage UPS as shown in the Fig. 9 is proposed in [23]. The first stage consists of an integrated battery charger which utilizes the flyback converter for charging the batteries, maintaining high power factor, and providing high frequency isolation. The second stage consists of boost inverter which supplies the regulated output voltage. Since the flyback converter may operate in discontinuous conduction mode, so the proposed topology is not suitable for high power applications.

3.3. Transformer-less UPS System

Nowadays with the development of advanced microcontrollers, and advancement in the power electronics, transformer-less UPS are getting popularity in the market. These UPS are less costly, highly efficient, and most importantly smaller in size than the transformer-based UPS. But the transformer-less UPS still has also some major limitation which needs to be addressed. This type of UPS is more likely to be effected by the transients and spikes caused by miscellaneous devices connected to the main utility grid [28]. The battery bank in transformer-less UPS is very high to achieve high DC link voltage, which increases the battery cost and lower the reliability of the system [29,30].

3.3.1. Four Leg Type Transformer-Less UPS

Four leg type transformer-less online UPS system has been proposed in [29]. The four leg type converter act as a rectifier, battery charger/discharger, and an inverter as shown in the Fig.10.

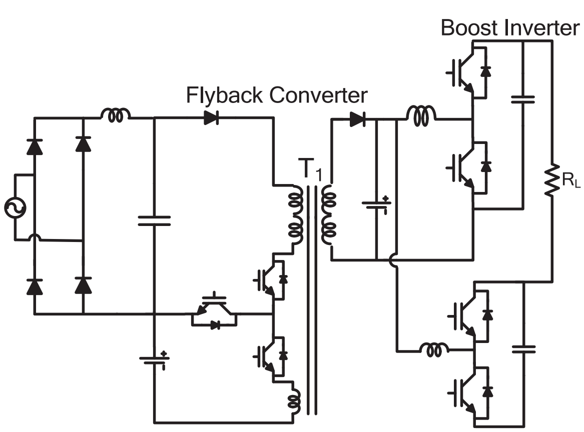

Fig. 9. UPS system proposed in [23].

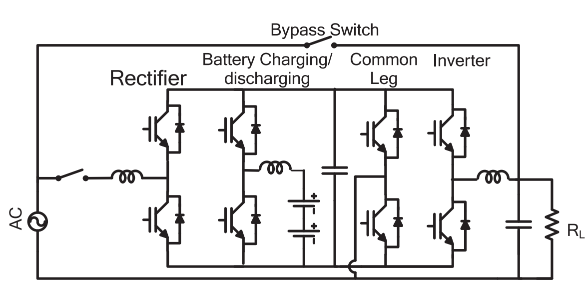

Fig. 10. Circuit Diagram of Four Leg type converter.

The common leg is switched at a line frequency while the rectifier, the battery charger/discharger, and the inverter are switched at their respective PWM signals. Since a bidirectional converter has been used, that charges the battery during normal mode and discharges the battery during the power failure mode. So the system has been operated without transformer, and the battery bank is reduced to 192 V.

3.3.2. Non-isolated UPS topology with 110/220 V input–output voltage

Another non-isolated online topology is proposed in [31] as shown in the Fig.11. This UPS system can be operated at two different voltage levels and can also provide two output of 110 V.The proposed UPS topology consist of a battery charger, three level boost rectifier, and a double half bridge inverter. The double half bridge inverter generates two independent 110 V AC output voltages. An autotransformer is used at the input of the system to enable the operation at 110 V. The DC link voltage in this topology is about 450 V and nine batteries connected in series form the battery bank, which is still very high.

3.3.3. Z-Source Inverter Based UPS System

Another transformer-less UPS topology has been proposed in [32–36] which utilizes a Z-source inverter. No dedicated boost converter has been used to step up the battery bank voltage as the Z source inverter combines the two stages of power conversions (DC–DC Step up converter and DC–AC inverter) into a single power conversion stage. Also a dual loop control scheme has been used to increase the transient response time of the system. No dead time in the PWM signal is required to prevent the switches of the same leg turning ON at the same time. Thus the distortion in the AC output voltage is reduced considerable. Thirty batteries connected in series provide the 360 V DC voltage at the input of the DC voltage. So the battery bank is very high, and is only feasible for high power applications.(Fig. 12)

3.3.4. Offline Transformer-less UPS System

Transformer-less topologies has been proposed in Offline UPS system as well. The system studied in [37] has been designed with reduced number of components which reduces the cost of the system. During charging mode, the uncontrolled rectifier converts

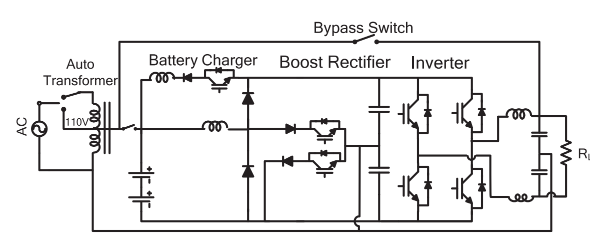

Fig. 11. Non-isolated UPS system.

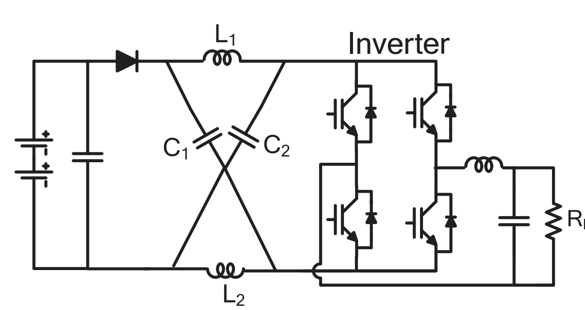

Fig. 12. Z-Source inverter UPS System.

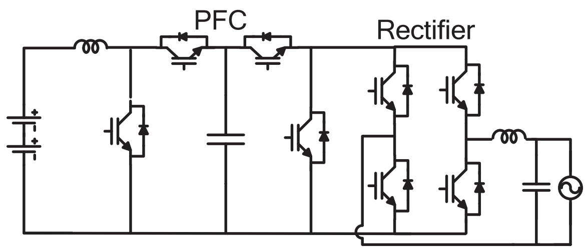

Fig. 13. Offline Transformer-less UPS system.

the line AC into DC link voltage, while the boost converter performs the PFC (Power Factor Correction) and the buck converter step down the voltage in order to charge the battery. During power failure, the boost converter steps up the battery bank voltage and the inverter converts it into the AC voltage to provide it to the load terminals.(Fig. 13)

3.4. *Comparison of transformer based and Transformer Less UPS system [38–42]*

Nowadays the transformer-based UPS system has been subjugated by the transformer-less UPS system because of its small size, light weight, and high efficiency. These UPS system offers highly compact and cost effective design for low power applications without using any bulky power transformer. Table 2 shows the comparison of different UPS configurations.

But which one is the most suitable UPS system according to the required circumstances? The answer is very complex. It requires understanding of the basic topologies and the particular requirement for the specific application. In selecting a UPS system, there is always a trade-off among certain features of the system, and the selectors always have to go for the features which are important for that specific application. Transformer based UPS system isolates the load from the faults generated in the main supply. In fact the transformer itself acts like a barrier and avert all the transients and spikes propagating to the DC bus from the main supply and vice versa. Also the transformer based UPS are more reliable and robust in operation with high Mean Time Before Failure (MTBF).

However the transformer based UPS are more expensive than transformer-less UPS system. Without input and output transformer, the cost of the transformer-less UPS system can be reduced to 30% or even more. Also the size and weight can be reduced to 50% in transformer-less UPS system as shown in the Table 2. Moreover the efficiency of the transformer-less UPS is about 10% greater than the transformer-based UPS system of the same specification due to the absence of the power frequency transformer.

4. Control Techniques

The control strategy is the most important part of all UPS systems. Parameters like THD of the output voltage, dynamic response to the transients and spikes; power factor correction, voltage and current regulation etc. are all dependent on the control strategy applied in the UPS system. Nowadays many modern control techniques have been proposed to provide regulated output voltage in all the circumstances. Broadly the control techniques can be classified as single control and multi loop control schemes

4.1. *Single Loop Control*

In single loop control scheme, the output voltage feedback loop is used to provide the well regulated output voltage [43]. The output voltage is compared with the reference signal to generate

Table 2
Comparison of different UPS system Configurations.

UPS topology	Properties							
	Number of Power stages	**Efficiency**	**Power Ratings**	**Power Factor**	**System Specification**	**Battery bank**	**Size & Weight**	**Applications**
Conventional Transformer Based UPS	two & Power Frequency Transformers	Less than 90%	Available with ratings greater than 750KVA	0.8 ~ 0.9	110 V/220 Vac	12 V ~ 360 V	Very High	From single computer to large data centres with load in MVA
Single Stage UPS system with trapezoidal AC supply [16]	Three & a Power Frequency Transformer	85%	1 KVA	0.9	110 Vac	80 V	High	Design for hybrid fiber/coax networks
Three Leg Type Converter UPS system [17]	three & leakage Transformers	87%	3 KVA	0.99	220 Vac	192 V	High	For High power applications,
A UPS with 110/220-V Input Voltage and High-Frequency Transformer Isolation [20]	Three & a High Frequency Transformer	86%	2 KV	0.7	110 Vac as well as 220 Vac	96 V	Medium	Low power applications
An on-line UPS system with electric isolation using BIFRED converter [21]	Three & a High Frequency Transformer	Less than 90%	< 1 KVA	high	110 Vac	48 V	smaller	Used for smaller loads
Two stage UPS with high power factor correction [23]	Two & High Frequency Transformer	84%	< 500 VA	0.99	110 Vac	48 V	Smaller	Low power Applications
Transformer-less Online UPS System [29]	Three Stages	96%	3 KVA	0.99	220 Vac	192 V	Smaller	Considerable high Power Application
Non-isolated UPS with 110/220 V input – output voltage [31]	Auto-transformer	86%	2.6 KVA	0.9	Both 110 Vac & 220Vac	108 V	Medium	Medium And High Power Application
Z Source Inverter Based UPS System [32]	Two Stages	> 90%	3KVA	-	220 Vac	360 V	Smaller	High Power Application

an error that is compensated by suitable controller. Though this system is simple to design and quiet inexpensive but its performance is poor in complex loading condition such as unbalanced and nonlinear loads.

4.2. Multi-loop System

Multi-loop control schemes are more suitable in order to get better performance. They are more robust and flexible in control, even in non-linear and unbalanced system [44,45]. A conventional multi-loop control scheme has been shown in the Fig. 14. In this control scheme, different parameters are used as a feedback to the controllers like filter inductor/capacitor current or output current and voltage. The outer loop uses output voltage as feedback signal; while the inner loop uses inductor or capacitor output filter current as the feedback signal. The feedback signal is compared with the reference signal to generate an error, which is compensated by the suitable compensator to achieve stable output. Similarly the output of the voltage loop is the reference for the current loop. Hence both the voltage and current stability is achieved using multi-loop system. Different high performance controllers have been developed by employing multi-loop feedback control scheme which provide excellent performance [46–51]. Such as dead beat control[47,52–54], Model Predictive control [48,55,56], Iterative learning control [49] etc.

4.2.1. Predictive Control

Predictive control technique has emerged as promising control technique for power inverters. Predictive control uses the system model to predict the future behaviour of the controller variables and respond according to predefined optimization criteria. Predictive control concepts are easy to understand and can handle the system with many constraints and non-linearity's. The predictive control can be classified in Deadbeat control and Model Predictive control. The detail of each controller is as follows.

4.2.1.1. Deadbeat Control. Deadbeat control scheme is one of the most popular schemes for UPS system [47]. In deadbeat control, the reference voltage is calculated during each sampling period using system model parameters, and is applied to follow the reference value in the next sampling instant. It offers fastest transient response because all the closed loop poles are placed near zero. This results in minimum settling time as few sampling steps are required. However the dead beat control is very complex and is highly sensitive to parameter variations, loading uncertainties, and steady state error. Moreover, performance of the deadbeat control also reduces due to unpredicted sources of disturbance, such as dead-times, dc-link voltage fluctuations, and so on, since there is no inherent integral action in the control structure. Fig. 15 shows a deadbeat control scheme for UPS system. A state observer is used to compute the delay while the load current is estimated using the disturbance observer. Any disturbance in the system is compensated by the state observer. In Deadbeat control the load current at time k is different to the reference current i^{ref}. This error is used for calculation the reference voltage V_o^{ref}, which is applied to the load at time k. Ideally at time k + 1, the load current will be equal to the reference current. This method gives better performance by reducing control sensitivity to model uncertainties, parameter mismatches, and noise on sensed variables

4.2.1.2. Model Predictive Control [55,57]:. Model Predictive Control (MPC) is considered as one of the important advancement in the process control engineering. Model Predictive control also knows as receding horizon control, provides high performance and stability in the control of UPS system. MPC is very flexible control in which different system constrains e.g current and voltage limitation, switching states, and non-linearity can be included in the optimization of the controller. A cost function is usually formulated considering different variables and weighting factor. A Switching state is selected in order to minimize the cost function and applied in the next switching state.

Fig. 16 shows the common model predictive control for the inverter of UPS system. The load current measured at instant K is used as input to the predictive model which derives the value of the current for the next sampling time, for each switching state of the inverter. At each instant K, cost function over a finite horizon of length N is minimized. The cost function can be derived by equation

$$i(x(k), u(k)) = F(x(K+N)) + \sum_{l=K}^{K+N-1} L(x(l), u(l)) \tag{1}$$

where F and L are the weighting functions which predicts the system behaviour e.g difference between the current reference and predicted value. The optimization of the moving horizon is performed at each sampling step i.e. at time $K+1$, the system state $x(K+1)$ is measured and the horizon is shifted to next step, where another optimization has been performed.

4.2.2. Repetitive control scheme

Repetitive control scheme has widely been used for the rejection of periodic disturbance in a dynamic system [46,58,59]. This scheme is based on the multiple feedback loops, with time delay unit which results in eliminating the periodic errors efficiently. But the limitations of this system include slow dynamic response, large memory requirements, and poor performance in non-periodic disturbance. Repetitive control has been introduced for the control of inverter with non-linear load. The steady state performance of the repetitive control is quite good but the dynamic response is not satisfactory because of long delay time between input and output. Therefore, repetitive control is normally incorporated with other feedback controller with fast dynamic response.

In repetitive controller, a periodic signal generator $\left(\frac{1}{z^N-1}\right)$ has been added in the closed loop system for exact tracking a

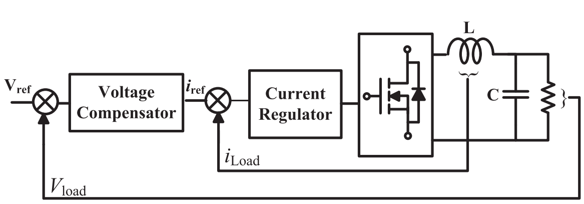

Fig. 14. Multi-loop control Scheme.

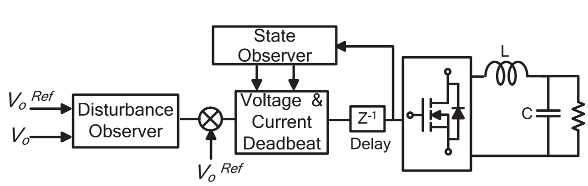

Fig. 15. Deadbeat Control for UPS system.

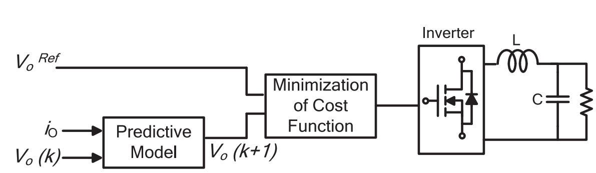

Fig. 16. Model Predictive control for UPS system.

reference signal. The repetitive controller eliminates all the harmonics below the Nyquist frequency by introducing infinite gain at the harmonic frequency [60].

A repetitive control system is shown in Fig. 17 The feedback control and repetitive control are complementary. The transfer function of repetitive control is given as

$$G_g(z) = \frac{k_g Z^{-N_1}}{1 - z^{-N}} G_f(Z) = \frac{k_g Z^{N_3}}{Z^N - 1} G_f(Z) \quad (2)$$

where k_g is the control gain and $G_f(Z)$ is a low-pass filter.

The conventional feedback controller offers fast response and robustness. However the feedback controller has no memory. Hence if there is any imperfection, it will keep repeating in all subsequent cycles. Similarly the repetitive controller stored pervious information in memory, and ensures steady-state zero error tracking by repetitive learning. But the zero error tracking took longer time. Hence the repetitive control scheme together with feedback controller ensures fast dynamic response of feedback controller and the high precision tracking ability of repetitive controller [61].

4.2.3. Iterative Learning Scheme

In Iterative Learning Control (ILS), the control command is adjusted at each iteration, thus converging to zero tracking error. The ILS aims to accomplish this result without the knowledge of the system. The system is examined at each cycle and is adjusted for the next repetition. But the design procedure of the ILS is very complex.

ILS can be used to eliminate tracking error caused by the periodic disturbance. The updated rule for ILC is given by

$$u_{i+1}(z) = u_i(z) + k\varnothing(z)e_i(z) \quad (3)$$

Where $u_i(z)$ is the Z transform of the command that is given to the system at repetition I, k is the learning gain and $\varnothing$ is the designed controller transfer function. While e_i is the z-transform of the racking error at repletion *i*.

$$e_{i+1}(z) = ((1 - k\varnothing(z)P(z))e_i(z) = T_f(z)e_i(z) \quad (4)$$

where T_f is the transfer function between the two consecutive repetitions. The error component at a particular frequency will decay over successive repetition if

$$|1 - k\varnothing\left(e^{jwT}\right)P(e^{jwT})| < 1 \quad (5)$$

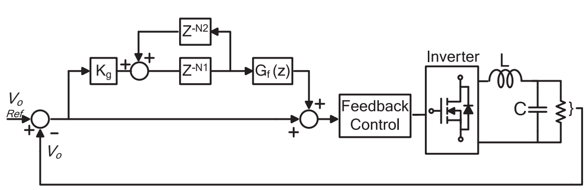

Fig. 17. Repetitive control for the UPS system.

If (4) is satisfied for all ω, then monotonic decay of the tracking error to zero will take place over successive cycles, and stable operation will be achieved. Table 3 shows the comparison between different multi-loop control schemes.

4.3. Non-linear Control Schemes

Non-linear controllers are more robust in operation, show good performance result as compared to linear controllers. However the implementation of this system is very complex. The most common non-linear control system is slide mode control and adaptive control for the UPS inverter control.

4.3.1. Slide Mode control:

For non-linear load, Slide Mode Control (SMC) [62,63] strategy has gained special interest. SMC has been widely implemented in the power inverters because of its effective performance against non-linear system with uncertainties. A major feature of the SMC is its robustness, good dynamic response, stability against non-linear loading conditions, and easy implementation. But the SMC has the disadvantages of inheriting the chattering phenomena i.e the undesirable oscillation with finite frequency and amplitude which leads to low control accuracy and high heat losses in the system [64].

A SMC has been presented in Fig. 18. SMC changes the dynamics of the system by employing the discontinuous control signal that forces the system to slide along the system normal behaviour [65]. The linear sliding surface function for the UPS inverter can be expressed as (6)

$$S = \lambda x_1 + x_2\lambda > 0 \quad (6)$$

where λ is a real constant and x1 is the voltage error, and its derivative is given by $x_2 = \dot{x}_1$. For the dynamic behaviour the (6) will be

$$S = \lambda x_1 + \dot{x}_1 = 0 \quad (7)$$

The objective of the control in (6) is to drive the trajectory of the system from any initial condition x(0) to the sliding surface S (x)=0. This trajectory is maintained at the sliding surface, and consequently directs the system towards the steady state condition. The slide mode control law for the inverter is given by

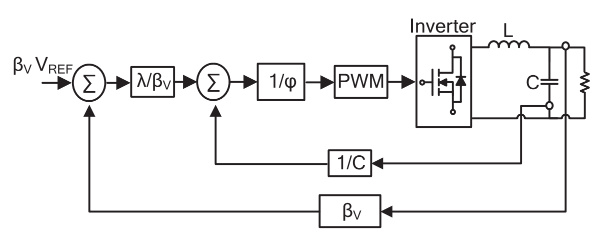

Fig. 18. Slide Mode Control scheme.

Table 3
Comparison of Different Multi-loop Control Schemes.

Control Scheme	Features				
	Controller Used	**Response Time**	**Performance**	**Sensor**	**Complexity**
Dead Beat Control [47]	ADMC401	0.5 ms	Not good for Non-linear loads	Output Voltage, Inductive current	Complex
Model Predictive Control [55]	TMS320C6713	Slow	Good	Output voltage, Filter current	Simple
Repetitive Control [46]	TMS320FS40	Slow	Excellent	Output Voltage	Complex
Iterative Learning Controller [49]	TMS320F240/MPC8240	Slow	Excellent	Output voltage	Complex
Neural Network Control [50]	Analog Circuit	Fast, 7.55 us	Good	Output Voltage	Complex
B-spline Network (BSN) Control [51]	DS1104	Fast, 7.78 us	Excellent	Output Voltage	Simple

equation

$$S = \lambda(V_{out} - V_{ref}) + \frac{1}{C}(i_C - i_{ref}) \tag{8}$$

The control law need to be tuned very precisely in order to achieve a trade-off between the tracking precision and robustness to the uncontrolled dynamics. The chattering phenomenon in the SMC is eliminated by using smoothed control law in narrow boundary layer. The smoothed control law applied to the pulse width modulator results in the fixed switching frequency of the inverter. The control scheme shows excellent performance with THD less than 1.7% for non-linear loads.

4.3.2. Adaptive Control

Adaptive control is another robust control scheme which automatically adjusts to the structural and environmental uncertainties. It does not need a priori information about the uncertain parameters rather the system characteristics are obtained on-line, while the system is operating. The adaptive control provides high performance with excellent voltage regulation for both unbalance and non-linear loads. Also it provides fast transient behaviour, small steady-state error, and low THD under sudden load change. However the computation complexity of adaptive control is very high.

Fig. 19 shows the block diagram of adaptive control law implemented in the inverter of the UPS system. A linear optimal load current observer is designed to accurately estimate load current. The load current observer is asymptotically stable in operation. The load current information is forwarded to adaptive control law. For deriving the adaptive control law, the control input are derived using both the compensated control terms and the feedback control term.

$$v_i = u_{ff} + u_{fb} \tag{9}$$

Applying the adaptive control law leads to equation

$$U_{ff} = \sum_{i}^{4} m_i p_i + v_L \tag{10}$$

where ‘m’ is the adaptive gain incorporate in the compensated control term v_i given in Eq. (9).

4.4. Modern Control System

Recently many state of the art control scheme has been proposed in [30,66–70]. Any advance control scheme should have the features of less execution time, low cost, high flexibility, and excellent performance with all the loading conditions. According to [67], selecting of a suitable control scheme depends on the optimum trade-off between cost, complexity, and waveform quality required for a particular application. A multi loop SPWM control scheme has been proposed in [66] as shown in the Fig. 20. The outer voltage loop controls the fundamental frequency components and the steady state RMS value of the output voltage using PI compensator. The first inner loop acts as voltage feed forward loop and provide fast transient response. The second inner loop compares the AC output to a reference created by the main loop, and an error signal is generated. This will correct the phase shift and improve the quality of the waveform. In the last, a current loop is added which provides overload protection and current limiting.

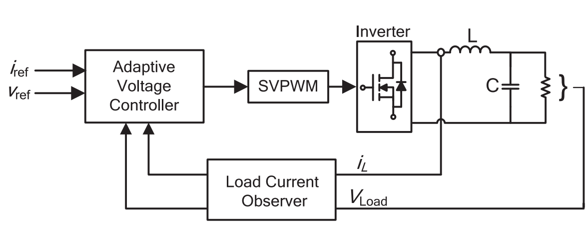

Fig. 19. Adaptive control for the UPS Inverter.

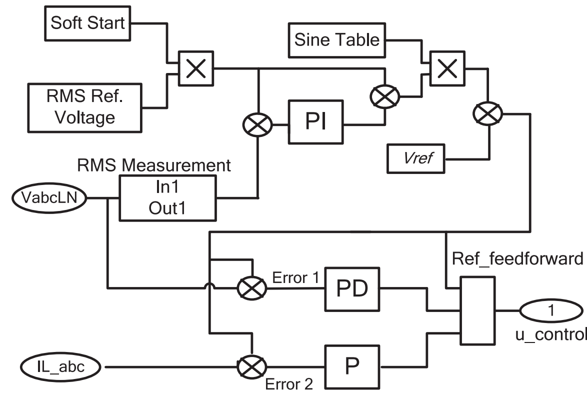

Fig. 20. Modern Control Scheme for UPS system.

Thus the outer voltage loop provides voltage regulation while the inner loop maintains THD, with excellent stability of the system. For linear loads, the controller achieve 0.3% THD while for non-linear loads, it achieve 3% THD. This control scheme can easily be implemented with less complexity and high response time of 10ms for any load.

Another robust tracking control of UPS Inverter has been proposed in [71]. The proposed controller utilizes state feedback and integral controller of the tracking error. The gain of the controller is designed keeping in view the parameters of uncertainties. Thus the controller shows fast tracking performance in uncertain conditions of the load. Also a one step ahead predictor has been introduced to reduce the time delay caused by computation and space vector modulation. Luenberger type observer is used to make the prediction of the inductor current, capacitor voltage and unmeasured disturbance. The prediction gain is calculated using Kalman filter and robust stat predictor. The proposed controller shows good performance under linear and non-linear loads with very low total harmonics distortion.

In [70] a multiple resonant control scheme has been proposed which provides very robust control framework to the UPS systems. In this scheme, output feedback controller has been designed using Linear Matrix Inequality (LMI) constraints. Thus efficient control parameters are derives to achieve a good compromised between transient performance, sinusoidal reference tracking and harmonics rejection. Multiple resonant controller attenuates the periodic disturbance efficiently resulting in low THD of the UPS output voltage. Table 4 shows the comparison of the modern control schemes used in the UPS systems.

5. Uninterruptible Power Supplies with hybrid storage system

Uninterruptible power supplies with batteries as storage source provides good performance during grid interruption and blackout by suppling instant backup energy. However batteries cannot provide backup for a very long period of time and have limited charge/discharge cycles. Also batteries contain toxic heavy metals such as cadmium, mercury, and lead which may cause serious environmental problems. Recently other methods of energy storage such as fuel cells, super-capacitor, and their combinations have gained popularity. The power sharing between these energy storage devices is a promising solution for improving system performance due to their dynamic behaviour and long life. Fig. 21 shows options of back-up power and their energy capacity. Many

Table 4
Comparison of Modern Control Schemes.

Ref Controller	[66] SPWM Controller	[70] Multiple Resonant Controller	[72] Synchronous Ref. Frame Voltage Control	[65] Fix Switch Frequency Slide Mode Control	[71] Robust Tracking Controller
THD(L)	1.1%	-	0.2%	1.1%	1.3%
THD(NL)	3.8%	2.7%	1.68%	1.7%	5.5%
Transient (ms)	60	16	1.0	0.5	-
Complexity	Medium	Complex	Complex	medium	Medium

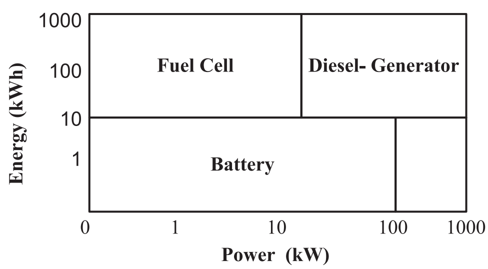

Fig. 21. Options of Backup power system.

reviews have focused on the composition, features, and performance of different energy storage systems [73–77]. In this portion brief review has been presented to highlight the performance of different energy systems in UPS applications.

5.1. *Fuel Cell/Batteries powered UPS system*

A UPS system with hybrid energy source has been presented in the [78–82]. In this system, fuel cell and battery bank is combined as such to ensure that there is sufficient energy available to provide backup to the external load. When there is interruption in the utility grid, the hydrogen gas will be supplied to the pack of fuel cell. Since fuel cell required some time to develop the required voltage hence cannot provide instant backup energy. To overcome this problem rechargeable battery or super-capacitor can be employed to respond quickly to the external load. A block diagram of the hybrid UPS system is illustrated in Fig. 22 [24].

The Fuel cell is the main source of energy. Batteries and supercapacitor act as secondary source of energy. Fuel cell is linked to DC-Bus through the DC–DC converter while all other sources are linked to the common DC-Bus through bidirectional converter. The bidirectional converter acts as battery charger during grid mode and discharger during backup mode of operation. The DC-Bus supply energy to the connect load through inverter.

The circuit diagram of the hybrid energy storage UPS system is shown in Fig. 23. A conventional boost converter is used to step up the fuel cell voltage to DC-link voltage. Bidirectional converter charges the battery/supercapacitor during grid mode (buck operation) and discharges the battery/supercapacitor during backup mode (boost mode), in order to provide stable supply to the DC-Bus. Different bidirectional converters have been presented in literature with both isolated and non-isolated topologies [83,84]. Bidirectional converter is selected depending on the conversion ratio, efficiency, and reliability of the system. H-bridge inverter is used to deliver regulated output AC voltage to the load. A fuel cell powered UPS system provides stable operation during utility interruption. Fuel cell is excellent replacement to the conventional UPS energy sources in near future. Supercapacitor module is incorporated to overcome transients such as instantaneous power fluctuations, slow dynamics of the fuel pre-processor and overload conditions. However the fuel cell technology still faces drawbacks such as high cost, slow response time, and sensitivity to low frequency ripples.

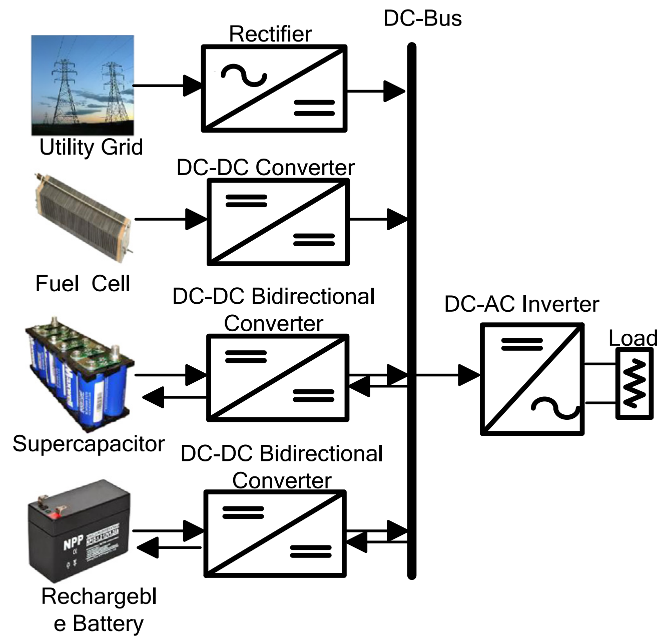

Fig. 22. Block Diagram of hybrid energy storage UPS system.

5.2. *Supercapacitor/Batteries powered UPS system [85–87]*

Normally batteries of UPS system provide backup power for 5–15 min until the generator starts and provides backup to the load. Supercapacitor provides backup for 5–15 s. Hence in application where the long backup is not required, supercapacitor can replace the battery storage system. Nowadays hybrid system of battery for higher energy and supercapacitor for higher power are combined to provide more reliable and high power. Table 5 shows the comparison of supercapacitor with lead-acid battery.

Introducing supercapacitor in parallel reduces the stress on the battery. Supercapacitor supply power during transient demand of power while batteries supplies during smooth demand of power. However the cost of supercapacitor are still very high and further research and investigation is required to balance the cost and performance of the supercapacitor based UPS system.

5.3. *Renewable energy Integrated UPS system*

Since global warming and greenhouse effect has reached to its threatening level, renewable energy is the only option for future energy requirement. Photovoltaic (PV) and wind energy are the most promising solution to supply energy in isolated areas. Uninterruptible power supplies with renewable energy resources connected with the utility grid provide more reliable and quality power to the connected load [88–90]. UPS with PV system is shown in the Fig. 24. The PV module is connected to the system through the DC–DC converter while the batteries and supercapacitor are connected to the DC-Bus using bidirectional

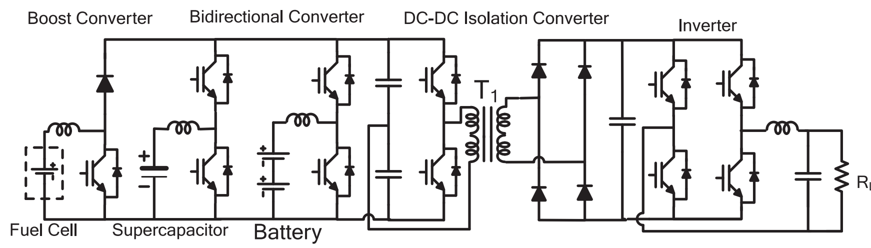

Fig. 23. Circuit Diagram of Hybrid Storage UPS system.

Table 5
Comparison of Lead-Acid Battery and Supercapacitor.

Properties	Lead acid battery	Supercapacitor
Specific energy density	10–100 Wh/kg	1–10 Wh/kg
Specific power density	< 1000 W/Kg	< 10,000 W/Kg
Cycle life	1000	85–98%
Charger/discharger efficiency	70–85%	0.3–30 s
Fast Charge time	1–5 H	0.3–30 s
Discharge time	0.3–3 h	0.3–30 s

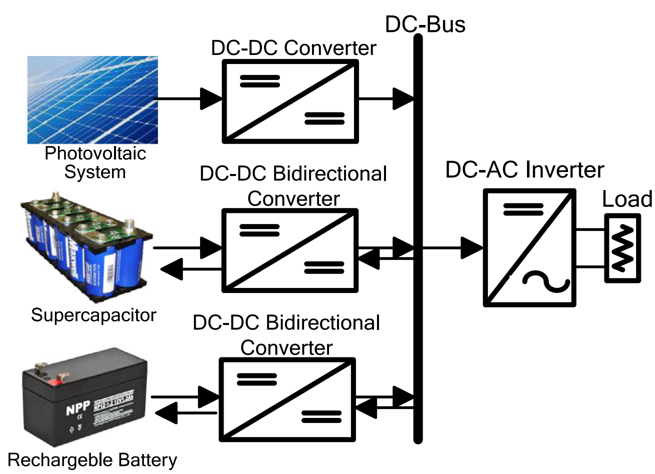

Fig. 24. UPS system with PV energy Source.

converter. The inverter supply AC voltage to the connected load. When there is a surplus energy available, it is stored in the connected battery bank and supercapacitor. Under the conditions, when load demand exceeds the generation or during night time, the stored energy is utilized to fulfil the requirements of the load. Supercapacitor is added in the system to provide fast dynamic regulation of the power. UPS with PV system helps in peak shearing, smoothing out load fluctuations, and making up for intermittent variation in renewable energy sources so as to make an efficient energy management in integrated systems [91].

6. Next Generation Uninterruptible Power Supply

In recent years, the concept of smart grid is getting famous and is considered as the next generation power grid [92–95]. Electricity generation using sustainable energy is environmental friendly and can be added to the smart grid. The distributive generating system provides standby power during grid interruption and load sharing during peak hours, thus it helps in cost reduction and reliable power delivery. In fact the concept of distributive generation system falls into the category of the UPS system.

An intelligent UPS system has been presented in [96,97] for the smart grid which is energy saving, reliable and flexile for

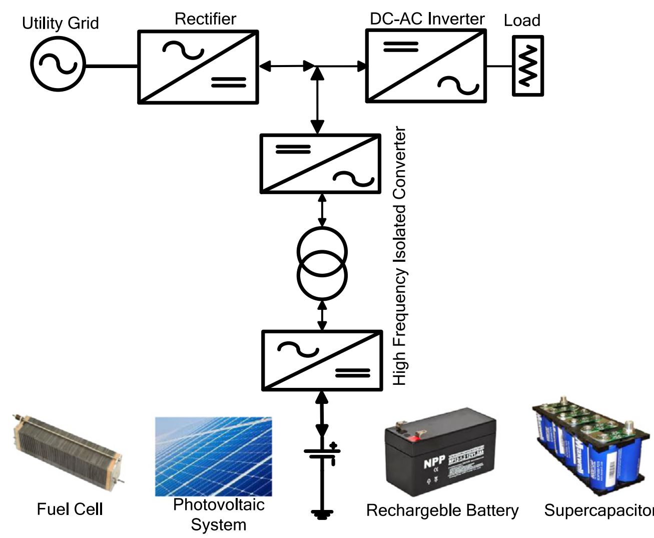

Fig. 25. Block Diagram of Intelligent UPS system.

accommodation of DG sources. Fig. 25 shows the block diagram of the next generation UPS system. The UPS system has high frequency converter which allows the parallel connection of the batteries with other Distributive generation (DG) system to the smart grid. Hence the proposed UPS system in addition to traditional operation can also realize the cyclic use of electrical power between the power grid and storage system. Due to its modular structure, it can be applied to motor drive, auxiliary power supplies for hybrid electrical vehicles and DG system.

Line interactive UPS systems proposed in [98,99] are designed for microgrid. The proposed system helped in improving the reliability, economy, and efficiency of the microgrid. Power can be exported to the grid when the tariffs are advantageous. Hence the UPS system can share power with in the microgrids in parallel with other DG Units. Multiple energy sources, multiple storages, and a highly reliable power conversion system work together to guarantee the uninterruptible power supply. But the idea of intelligent UPS system still needs extensive research in order to realize the concept in smart grid and micro grid.

7. Selection Considerations of UPS system for specific application

With so many choices of the UPS system available to choose from, which is the most suitable for your circumstances? Selecting a particular type and configuration of UPS depends upon the following factors. (1) Power requirement, (2) Power factor, (3) Cost, (4) Size and Weight, (5) Grid environment, (6) Reliability, (7) Protection, (8) Required level of Power quality, and (9) Size of the battery bank.

The Process of selecting a UPS system consists of seven steps. (1) Determining the need of UPS system, (2) Calculating the Power requirement of UPS system, (3) Selecting type of UPS system, (4) Select configuration of UPS system, (5) Safety of UPS system, (6) Availability of UPS system, (7) Is selected UPS system affordable. Fig. 26 shows the flow chart for selection of a UPS system for particular application.

7.1. Determining the need of UPS system

The selection of UPS system is strongly dependent on the application for which the system is chosen. Applications such as hospital life support and medical equipment, military equipment's, and communication devices cannot tolerate any power interruption even for very short period of time. UPS system required for such application should provide backup until the utility grid power is restored. For data centres, the backup may require for only few moments until the devices are shutdown. Surveying the history of commercial outages by power companies can better provide statistics about selection of UPS system.

7.2. Calculating the Power requirement of UPS system

Specification such as load kVA, power factor, inrush current, load voltage, number of phases and frequency, and backup time is required to determine the size of the UPS system. Load kVA can be calculated as $(V \times I)/1000$ for single phase and $(1.73 \times V \times I)/1000$ for three phase system. The load power factor should be in the range of 0.7–1 depending upon the load. Battery sizing depends on the size of the load and duration of backup requirement until the critical load is safely shutdown. Ampere-hour (AH) capacities decrease as the rate of discharge increases. For varying load, the summation of the ampere-hour of each load gives the approximate size of the battery.

7.3. Selecting type of UPS system

Selection of UPS system depends upon the power quality, protection, efficiency, volumetric size, and weight of the system. The details discussion of different type of UPS system has been done in Section 2. Table 6 summarizes the features of different type of UPS system.

7.4. Select configuration of UPS system

The level of protection and the power requirement of the load determine the type and configuration of the UPS system. Transformer-based UPS are more suitable for high power application. They are more suitable to provide protection even in the polluted grid environment to more sensitive equipment like medical equipment's and data centres because of the galvanic isolation.

While the transformer-less UPS systems are cheaper, with smaller size, and are suitable for low power applications. They are more suitable for circumstances, where the grid supply is less polluted. Similarly the complex control system also escalates the cost of the UPS system. So the choice of the UPS system is determined by the balance between the performance and cost, taking into consideration the acceptable level of other factors which best suits the circumstances. Table 7 correlates the properties of UPS system with the different topologies of UPS system.

7.5. Safety of UPS system

Safety should be given up most importance before selecting any UPS system. For safety it is preferred to follow the codes and standards adopted by government and commercial agencies. Battery bank needs special care and safety for its sound operation [100].

7.6. Availability of UPS system

Since UPS system provides back up to critical load without any interruption [101]. The availability and reliability of the system is very crucial. The availability of the UPS system is defined by equation

$$A_{UPS} = \frac{MTBF}{MTBF + MTTR} \quad (11)$$

where $A_{UPS}$is the availability of the UPS system, MTBF is the Mean Time Before Failure, and MTTR is the Mean Time To Repair. Reliability of the UPS system can be improved by introducing the redundant units in parallel where each one is capable of sharing the connected load [102,103].

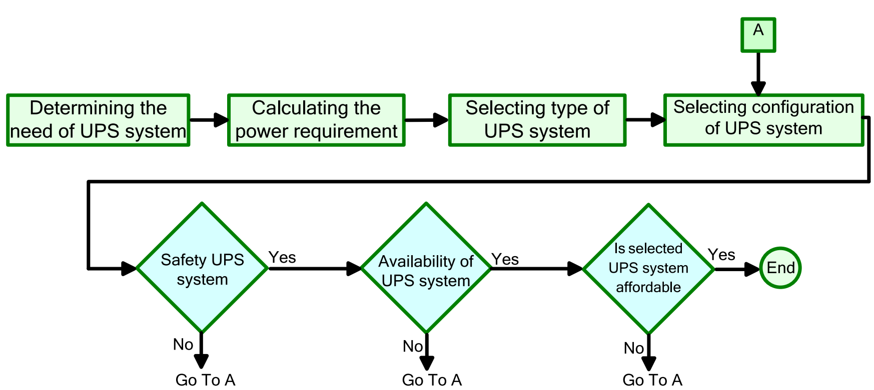

Fig. 26. Flow diagram for selecting the UPS system.

Table 6
Comparison of Different Type UPS system.

	Practical Power Range	Voltage Conditioning	Cost per VA	Efficiency	Inverter always operating
Offline UPS System	0–0.5	Low	low	Very High	No
Line Interactive UPS system	0.5–5	Design implementation	Medium	Very high	Design Dependent
Online UPS system	5–5000	High	Medium	Medium	Yes

Table 7
Selection of UPS System.

Recommended Type of UPS Topology	Power Level (KVA)	Grid Condition	Load Condition	Capital Cost	Weight& Volume	Power Quality	Efficiency
Transformer Based	1–10	Polluted	Variable	High	High	Average	Low
High Frequency		Less Polluted		Medium	Medium	Good	High
Transformer-less		Clean	Almost Fix	Low	Small	Excellent	High
Transformer Based	10–50	Polluted	Variable	High	High	Average	Medium
High Frequency		Less Polluted	Variable	Medium	Medium	Good	High
Transformer-less		Clean	Fix	Low	Small	Excellent	High
Transformer Based	50–200	Polluted	Variable	Very high	High	Average	Low
High Frequency		Clean	Fix	High	Medium	Average	Medium

Table 8
Typical 3-Ø UPS System Specification by *ANSI/IEEE 446–1987* [105].

Input (Rectifier/charger)	
Voltage	208 V or 480 V, ± l0%, 3-phase
Power factor	Minimum 0.8 at rated load
Frequency	50 or 60 Hz, t5%
Harmonic Contents in Current	10% (5% preferred)
Start-up current Limiting	Maximum 25% of full-load current (energizing rectifier transformer with inverter at no load)
Steady State Current limit	Adjustable, with two standard settings:1) For utility power, 125% rated load, 2) For emergency power, 100% rated load plus 5 kVA
Output (Inverter)	
Voltage	208 V or 480 V, 3-phase, 3- or 4-wire
Regulation	1) ± 2% for balanced load, 2) ± 3% for 20% unbalanced load (100% or 80%)
Line Drop Compensation	0 to 5%, adjustable
Transient Response	1) ± 5% for loss or return of ac input power, 2) ± 8% for 50% load step, 3) ± 10% for bypass or return from bypass
Harmonic content of voltage	4% total, 3% any single harmonic
Frequency	50 or 60 Hz
Current capability	1) Overload 125% for 10 m and 150% for 10 s
	Fault clearing 150% to 300% for 10 cycles, maximum limited for self-protection
DC Link (Battery)	
Battery type	Lead-acid or nickel-cadmium (NICAD)
Recharge time	10 times discharge time
Energy storage capacity	Sized to requirement (normally 15 min)

7.7. *Is selected UPS system affordable*

The cost of UPS system varies depending upon the type, configuration, protection, backup time, and extra additional features of the system. Mostly sophisticated system having automatic monitoring, fast switching, and control functions require additional components, adding to the complexity and cost of the system. Cost analysis can only be done when the first six steps are completed.

8. Performance Evaluation of UPS System

Several features are essential to analyse the performance of the UPS system. These features include input power factor, THD of the output voltage, transient response time and transfer time from utility grid mode to backup mode and vice versa. Hence the performance indicator of the UPS system is proposed to be according to the specified standards. Table 8 shows the specifications of a 3-Ø UPS system define by IEEE standard *ANSI/IEEE* 446–1987. Experimental results of a 2 kVA laboratory prototype of online UPS system have been presented to demonstrate clearly the performance of UPS system. The input voltage and current of the UPS system is shown in the Fig. 27. The power factor of the input current is close to unity with minimum THD. According to the IEEE standard *ANSI/IEEE* 446–1987, minimum power factor is 0.8 at the rated load and harmonics content less than 5% is preferred for the input rectifier of the UPS system.

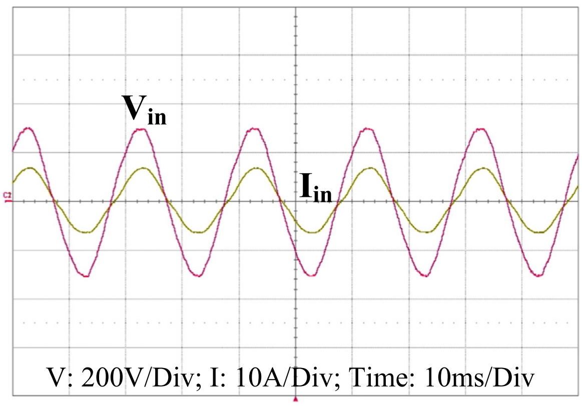

Fig. 27. Input Voltage and Current waveform.

The output voltage and current of the inverter of UPS system should be well regulated, with THD less than 5% for both nonlinear and unbalanced load. In addition, the inverter should exhibit excellent response against sudden change in the load. Fig. 28 shows output voltage and current of the inverter of UPS system where the THD is less than 3% for both the linear and non-linear load well below according to the standard (IEEE standard 4% total & 3% for each harmonic). Fig. 29 shows the step response of the inverter for change of load from 0 to 100% and vice versa. Fig. 30 shows the dynamic deviation of the output voltage for the addition and removal of the step linear load. The dynamic behaviour of the controller should not exceed the classification 1 of *IEC62040-3* standard

The transfer time from grid mode to backup powered mode is very important to evaluate the performance of UPS system. Online UPS system has negligible transfer time, while line-interactive and offline UPS system inherits some transfer time during transition switching of UPS operating modes. Fig. 31 and Fig. 32 show the experimental waveform of the step change from grid mode to backup mode and vice versa.

9. Future Trends

With the development in the advanced microcontrollers and fast switching devices, ever most capable UPS systems have been proposed with high performance, greater efficiency, and more importantly at lower costs. Transformer-based UPS systems have been developed to a mature level and are now available even in megawatt range, utilized for varying applications. Besides, a considerable development has been made in transformer-less UPS

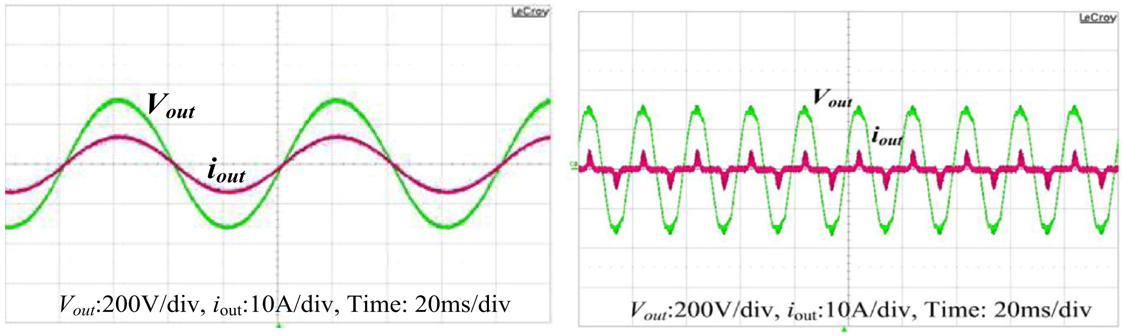

Fig. 28. Output Voltage and Current for linear load and non-linear load.

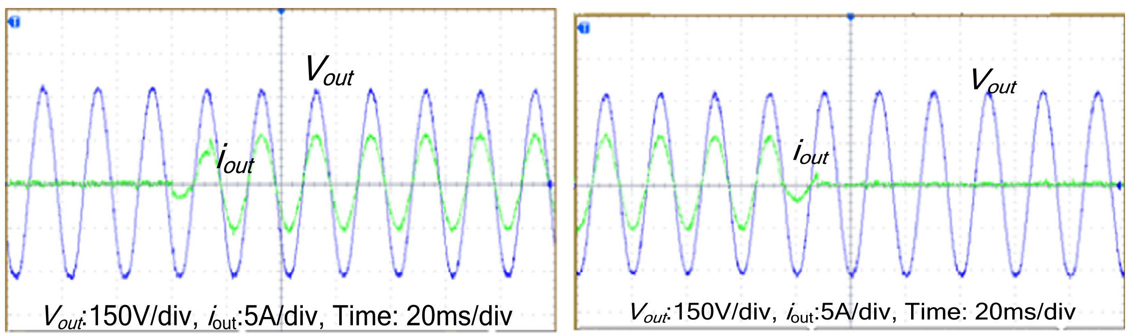

Fig. 29. Experimental waveform of step change from 0% to 100% and 100% to 0.

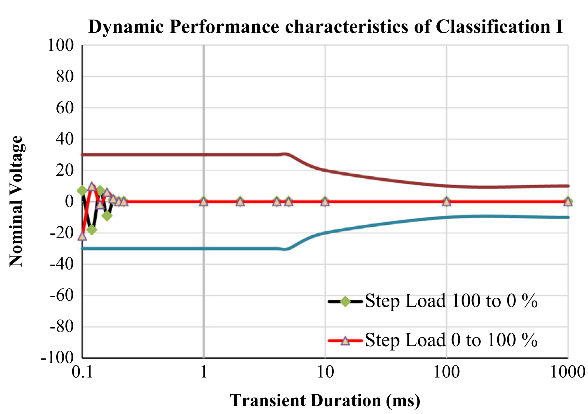

Fig. 30. Output Dynamic performance of the UPS Inverter.

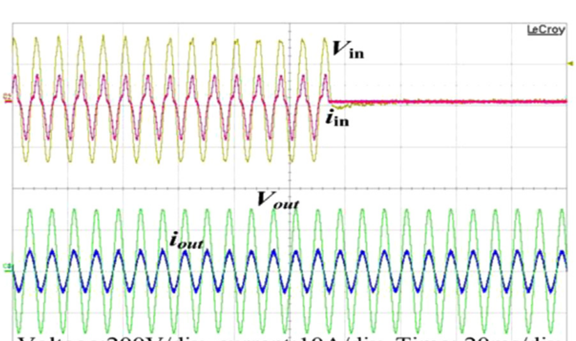

Fig. 31. Transition from Normal to Battery Powered Mode. Input Voltage V_{in} and Current I_{in}, Output Voltage V_{out} and Current I_{out}.

systems. New trends are heading towards the development of efficient control techniques to ensure fast transient and dynamic response, low THD, good voltage regulation, and stability against load variations.

Further improvement in the UPS technology in terms of replacing the conventional storage with fuel cells will be a real boost for UPS in low power applications [5,104]. Fuel cells have high specific energy, high reliability, and are environment friendly as compared to conventional storage systems. UPS systems that use the fuel cell in combination with the super-capacitor are also not that extensively investigated. Recognizing the advantages of the hybrid system, we can expect more advanced UPS system, with added functionality and better performance.

10. Conclusion

In this paper, a review of UPS systems has been presented to explain the various configurations, control strategies, and comparisons of important UPS topologies. A topological classification of the UPS system has been discussed with their performance, efficiency, advantages, and disadvantages. Comparative analysis of different systems and their control schemes have been presented to provide useful information, which helps in easy selection of control scheme for a particular application. Model predictive control shows excellent performance for the control of the inverter. Non-linear control schemes can also be adopted for non-linear loads though their implementation is complex. Hybrid energy sources UPS systems and their application in smart grid bring new direction for research and development in this field. Power sharing between different energy storage devices adds dynamic stability and reliability to the performance of UPS system. Depending upon the grid environment, power rating, volumetric size, and backup time a suitable topology can be selected. Performance evaluation

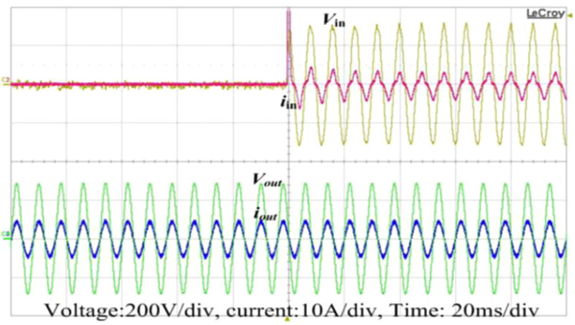

Fig. 32. Transition from Battery power mode to Normal mode, Input Voltage V_{in} and Current I_{in}, Output Voltage V_{out} and Current I_{out}.

of the UPS system has been presented and important features for selection of UPS system have been explained such as input power factor, output voltage, step response, and transient time for change of modes (Grid and Backup). This review will be very useful reference for the researchers, designers, users, and manufacturers working on the UPS system.

Acknowledgment

The authors would like to acknowledge the financial support from University of Malaya. This research was carried under the High Impact Research Grant (UM.C/HIR/MOHE/ENG/24)scheme and Bright Spark Unit, University of Malaya.

References

[1] Gurrero J, De Vicuna LG, Uceda J. Uninterruptible power supply systems provide protection. IEEE Ind Electron Mag 2007;1:28–38.
[2] Windhorn A. A hybrid static/rotary UPS system. IEEE Trans Ind Appl 1992;28:541–5.
[3] King A, Knight W. Uninterruptible Power Supplies and Standby Power Systems. McGraw-Hill; 2003.
[4] El Fathi A, Nkhaili L, Bennouna A, Outzourhit A. Performance parameters of a standalone PV plant. Energy Convers Manag 2014;86:490–5.
[5] De Bernardinis A, Péra M-C, Garnier J, Hissel D, Coquery G, Kauffmann J-M. Fuel cells multi-stack power architectures and experimental validation of 1kW parallel twin stack PEFC generator based on high frequency magnetic coupling dedicated to on board power unit. Energy Convers Manag 2008;49:2367–83.
[6] Per Grandjean-Thomsen. UPS System Design Handbook. Merlin Gerin (Aust) Pty Limited. 1992.
[7] Deng H, Oruganti R, Srinivasan D. Modeling and control of single-phase UPS inverters: a survey. IEEE International Conference on Power Electronics and Drives Systems, 2005 PEDS; 2005. p. 848-53.
[8] Niroomand M, Karshenas H. Review and comparison of control methods for uninterruptible power supplies. 2010 1st: IEEE Power Electronic & Drive Systems & Technologies Conference (PEDSTC); 2010. p. 18-23.
[9] Solter W. A new international UPS classification by IEC 62040-3. 2002 IEEE INTELEC 24th Annual International Telecommunications Energy Conference; 2002. p. 541-5.
[10] Racine MS, Parham JD, Rashid M. An overview of uninterruptible power supplies. Power Symposium, 2005 Proceedings of the 37th Annual North American: IEEE; 2005. p. 159-64.
[11] Bekiarov SB, Emadi A. Uninterruptible power supplies: classification, operation, dynamics, and control. Applied Power Electronics Conference and Exposition, 2002 APEC 2002 Seventeenth Annual IEEE: IEEE; 2002. p. 597-604.
[12] Karve S. Three of a kind [UPS topologies, IEC standard]. IEE Rev 2000;46:27–31.
[13] Kwon B-H, Choi J-H, Kim T-W. Improved single-phase line-interactive UPS. IEEE Trans Ind Electron 2001;48:804–11.
[14] Holtz J, Lotzkat W, Werner K-H. A high-power multitransistor-inverter uninterruptable power supply system. IEEE Trans Power Electron 1988;3:278–85.
[15] Botterón F, Pinheiro H. A three-phase UPS that complies with the standard IEC 62040-3. IEEE Trans Ind Electron 2007;54:2120–36.
[16] Jain PK, Espinoza JR, Jin H. Performance of a single-stage UPS system for single-phase trapezoidal-shaped AC-voltage supplies. IEEE Trans Power Electron 1998;13:912–23.
[17] Choi J-H, Kwon J-M, Jung J-H, Kwon B-H. High-performance online UPS using three-leg-type converter. IEEE Trans Ind Electron 2005;52:889–97.
[18] Chiang S, Lee T-S, Chang J. Design and implementation of a single phase three-arms rectifier inverter. IEE Proceedings-: IET Electric Power Applications; 2000. p. 379-84.
[19] Jacobina CB, Oliveira TM, da Silva ERC. Control of the single-phase three-leg AC/AC converter. IEEE Trans Ind Electron 2006;53:467–76.
[20] Torrico-Bascopé RP, Oliveira D, Branco CG, Antunes FL, Cruz CM. A high frequency transformer isolation 110V/220V input voltage UPS system. Applied Power Electronics Conference and Exposition, 2006 APEC'06 Twenty-First Annual IEEE: IEEE; 2006. p. 7 pp.
[21] Nasiri A, Nie Z, Bekiarov SB, Emadi A. An on-line UPS system with power factor correction and electric isolation using BIFRED converter. IEEE Trans Ind Electron 2008;55:722–30.
[22] Hirachi K, Yoshitsugu J, Nishimura K, Chibani A, Nakaoka M. Switched-mode PFC rectifier with high-frequency transformer link for high-power density single phase UPS. 28th Annual IEEE Power Electronics Specialists Conference, 1997 PESC'97 Record; 1997. p. 290-6.
[23] Vázquez N, Aguilar C, Arau J, Cáceres RO, Barbi I, Gallegos JA. A novel uninterruptible power supply system with active power factor correction. IEEE Trans Power Electron 2002;17:405–12.
[24] Tao H, Duarte JL, Hendrix MA. Line-interactive UPS using a fuel cell as the primary source. IEEE Trans Ind Electron 2008;55:3012–21.
[25] Torrico-Bascopé R, Oliveira D, Branco C, Antunes F. A PFC pre-regulator with 110 V/220 V input voltage and high frequency isolation for UPS applications. 31st Annual Conference of IEEE Industrial Electronics Society, 2005 IECON; 2005. p. 6 pp.
[26] Yamada R, Kuroki K, Shinohara J, Kagotani T. High-frequency isolation UPS with novel SMR. International Conference on Industrial Electronics, Control, and Instrumentation, 1993 Proceedings of the IECON'93; 1993. p. 1258-63.
[27] Pinheiro H, Jain PK. Series-parallel resonant UPS with capacitive output DC bus filter for powering HFC networks. IEEE Trans on Power Electron 2002;17:971–9.
[28] Koffler R. Transformer or transformerless UPS? Power Eng 2003;17:34–6.
[29] Park J-K, Kwon J-M, Eung-Ho K, Kwon B-H. High-performance transformerless online UPS. IEEE Trans Ind Electron 2008;55:2943–53.
[30] Daud MZ, Mohamed A, Hannan M. An improved control method of battery energy storage system for hourly dispatch of photovoltaic power sources. Energy Convers Manag 2013;73:256–70.
[31] Branco CG, Cruz CM, Torrico-Bascopé RP, Antunes FL, Barreto LH. A transformerless single phase on-line UPS with 110 V/220 V input output voltage. 2006 APEC'06 Twenty-First Annual IEEE Applied Power Electronics Conference and Exposition; 2006. p. 7 pp.
[32] Zhou ZJ, Zhang X, Xu P, Shen WX. Single-phase uninterruptible power supply based on Z-source inverter. IEEE Trans Ind Electron 2008;55:2997–3004.
[33] Peng FZ, Yuan X, Fang X, Qian Z. Z-source inverter for adjustable speed drives. IEEE Power Electron Lett 2003;1:33–5.
[34] Shen M, Joseph A, Wang J, Peng FZ, Adams DJ. Comparison of traditional inverters and Z-source inverter. 2005 PESC'05 IEEE 36th Power Electronics Specialists Conference; 2005. p. 1692-8.
[35] Holland K, Shen M, Peng FZ. Z-source inverter control for traction drive of fuel cell-battery hybrid vehicles. 2005 IEEE Fourtieth IAS Annual Meeting Conference Record of Industry Applications Conference; 2005. p. 1651-6.
[36] Peng FZ. Z-source inverter. IEEE Trans Ind Appl 2003;39:504–10.
[37] Marei MI, Abdallah I, Ashour H. Transformerless Uninterruptible Power Supply with Reduced Power Device Count. Electr Power Compon Syst 2011;39:1097–116.
[38] Al Dubaikel F. Comparison between transformer-based Vs. transformer-less UPS systems. 2011 IEEE Symposium on Industrial Electronics and Applications (ISIEA); 2011. p. 167-72.
[39] Gunes I, Ustuntepe B, Hava A. Modern transformerless uninterruptable power supply (UPS) systems. ELECO 2009 International Conference on Electrical and Electronics Engineering; 2009. p. I-316-I-20.
[40] Spears E, Oughton G. Transformer-Free UPS Design: Small Footprint, Big Power. Battery Power Mag 2008:12.
[41] Comparing Transformerless to Transformer-based UPS design. Emerson Network Power
[42] Neudorfer J. Will a transformerless UPS work for your data center? Data Center Management Advisory Newsletter.
[43] Karshenas H, Niroomand M. Design and implementation of a single phase inverter with sine wave tracking method for emergency power supply with high performance reference. ICEMS 2005 Proceedings of the Eighth International Conference on Electrical Machines and Systems; 2005. p. 1232-7.
[44] Abdel-Rahim NM, Quaicoe JE. Analysis and design of a multiple feedback loop control strategy for single-phase voltage-source UPS inverters. IEEE Trans Power Electron 1996;11:532–41.
[45] Jung S-L, Ying-Yu Tzou. Multiloop control of an 1-phase PWM inverter for ac power source. IEEE PESC Conf Rec 1997:706–12.
[46] Zhang K, Kang Y, Xiong J, Chen J. Direct repetitive control of SPWM inverter for UPS purpose. IEEE Trans Power Electron 2003;18:784–92.
[47] Mattavelli P. An improved deadbeat control for UPS using disturbance observers. IEEE Trans Ind Electron 2005;52:206–12.
[48] Cortés P, Ortiz G, Yuz JI, Rodríguez J, Vazquez S, Franquelo LG. Model predictive control of an inverter with output filter for UPS applications. IEEE Trans Ind Electron 2009;56:1875–83.

[49] Deng H, Oruganti R, Srinivasan D. Analysis and design of iterative learning control strategies for UPS inverters. IEEE Trans Ind Electron 2007;54:1739–51.
[50] Xiao S, Chow MHL, Leung FHF, Dehong X, Yousheng W, Lee YS. Analogue implementation of a neural network controller for UPS inverter applications. IEEE Trans Power Electron 2002;17:305–13.
[51] Deng H, Oruganti R, Srinivasan D. Neural controller for UPS inverters based on B-spline network. IEEE Trans Ind Electron 2008;55:899–909.
[52] Zhang Y, Xie W, Zhang Y. Deadbeat direct power control of three-phase pulse-width modulation rectifiers. IET Power Electron Inst Eng Technol 2014:1340–6.
[53] Nasiri A. Digital control of three-phase series-parallel uninterruptible power supply systems. IEEE Trans Power Electron 2007;22:1116–27.
[54] Buso S, Fasolo S, Mattavelli P. Uninterruptible power supply multiloop control employing digital predictive voltage and current regulators. IEEE Trans Ind Appl 2001;37:1846–54.
[55] Cortés P, Ortiz G, Yuz J, Rodríguez J, Vazquez S, Franquelo LG. Model predictive control of an inverter with output filter for UPS applications. IEEE Trans Ind Electron 2009;56:1875–83.
[56] Rodriguez J, Kazmierkowski MP, Espinoza JR, Zanchetta P, Abu-Rub H, Young H, et al. State of the art of finite control set model predictive control in power electronics. IEEE Trans Ind Inform 2013;9:1003–16.
[57] Kim S-K, Park CR, Yoon T-W, Lee YI. Disturbance-observer-based model predictive control for output voltage regulation of three-phase inverter for uninterruptible-power-supply applications. Eur J Control 2015;23:71–83.
[58] Chen S, Lai Y, Tan S-C, Tse CK. Analysis and design of repetitive controller for harmonic elimination in PWM voltage source inverter systems. IET Power Electron 2008;1:497–506.
[59] Chen D, Zhang J, Qian Z. An improved repetitive control scheme for grid-connected inverter with frequency-adaptive capability. IEEE Trans Ind Electron 2013;60:814–23.
[60] Zhou K, Wang D, Zhang B, Wang Y. Plug-in dual-mode-structure repetitive controller for CVCF PWM inverters. IEEE Trans Ind Electron 2009;56:784–91.
[61] Zhou K, Wang D. Digital repetitive controlled three-phase PWM rectifier. IEEE Trans Power Electron 2003;18:309–16.
[62] Muthu S, Kim J. Discrete-time sliding mode control for output voltage regulation of three-phase voltage source inverters. Applied Power Electronics Conference and Exposition, 1998 APEC'98 Conference Proceedings 1998, Thirteenth Annual: IEEE; 1998. p. 129-35.
[63] Rech C, Pinheiro H, Grundling HA, Hey HL, Pinheiro JR. A modified discrete control law for UPS applications. IEEE Trans Power Electron 2003;18:1138–45.
[64] El Fadil H, Giri F. Reducing chattering phenomenon in sliding mode control of Buck-Boost power converters. Industrial Electronics, 2008 ISIE 2008 IEEE International Symposium on: IEEE; 2008. p. 287-92.
[65] Abrishamifar A, Ahmad AA, Mohamadian M. Fixed switching frequency sliding mode control for single-phase unipolar inverters. IEEE Trans Power Electron 2012;27:2507–14.
[66] Tamyurek B. A high-performance SPWM controller for three-phase UPS systems operating under highly nonlinear loads. IEEE Trans Power Electron 2013;28:3689–701.
[67] Teodorescu R, Blaabjerg F, Liserre M, Loh PC. Proportional-resonant controllers and filters for grid-connected voltage-source converters. IEE Proceedings-Electric Power Appl 2006;153:750–62.
[68] Shen J-M, Jou H-L, Wu J-C. Transformerless single-phase three-wire line-interactive uninterruptible power supply. IET Power Electron 2012;5:1847–55.
[69] Jiang S, Cao D, Li Y, Liu J, Low-THD Peng FZ. fast-transient, and cost-effective synchronous-frame repetitive controller for three-phase UPS inverters. IEEE Trans Power Electron 2012;27:2994–3005.
[70] Pereira LFA, Vieira JF, Bonan G, Coutinho D, daSilva JMG. Multiple resonant controllers for uninterruptible power supplies—A systematic robust control design approach. IEEE Trans Ind Electron 2014;61:1528–38.
[71] Lim JS, Park C, Han J, Lee Y. Robust Tracking Control of a Three-Phase DC-AC Inverter for UPS Applications. IEEE Trans Ind Electron 2014;61:4142–51.
[72] Monfared M, Golestan S, Guerrero JM. Analysis, design, and experimental verification of a synchronous reference frame voltage control for single-phase inverters. IEEE Trans Ind Electron 2014;61:258–69.
[73] Hadjipaschalis I, Poullikkas A, Efthimiou V. Overview of current and future energy storage technologies for electric power applications. Renew Sustain Energy Rev 2009;13:1513–22.
[74] Ibrahim H, Ilinca A, Perron J. Energy storage systems—characteristics and comparisons. Renew Sustain energy Rev 2008;12:1221–50.
[75] Ren G, Ma G, Cong N. Review of electrical energy storage system for vehicular applications. Renew Sustain Energy Rev 2015;41:225–36.
[76] Mekhilef S, Saidur R, Safari A. Comparative study of different fuel cell technologies. Renew Sustain Energy Rev 2012;16:981–9.
[77] Shi K, Li H, Hu C, Xu D. Topology of super uninterruptible power supply with multiple energy sources. Power Electronics and ECCE Asia (ICPE-ECCE Asia), 2015 9th International Conference on: IEEE; 2015. p. 1742-9.
[78] Zhang W, Xu D, Li X, Xie R, Li H, Dong D, et al. Seamless transfer control strategy for fuel cell uninterruptible power supply system. IEEE Trans Power Electron 2013;28:717–29.
[79] Zhan Y, Guo Y, Zhu J, Wang H. Intelligent uninterruptible power supply system with back-up fuel cell/battery hybrid power source. J Power Sources 2008;179:745–53.
[80] Choi W, Howze JW, Enjeti P. Fuel-cell powered uninterruptible power supply systems: Design considerations. J Power Sources 2006;157:311–7.
[81] Zhan Y, Guo Y, Zhu J, Li L. Performance comparison of input current ripple reduction methods in UPS applications with hybrid PEM fuel cell/supercapacitor power sources. Int J Electr Power Energy Syst 2015;64:96–103.
[82] Zhan Y, Guo Y, Zhu J, Li L. Power and energy management of grid/PEMFC/battery/supercapacitor hybrid power sources for UPS applications. Int J Electr Power Energy Syst 2015;67:598–612.
[83] Ahmed O, Bleijs J. An overview of DC–DC converter topologies for fuel cell-ultracapacitor hybrid distribution system. Renew Sustain Energy Rev 2015;42:609–26.
[84] Kirubakaran A, Jain S, Nema R. A review on fuel cell technologies and power electronic interface. Renew Sustain Energy Rev 2009;13:2430–40.
[85] Lahyani A, Venet P, Guermazi A, Troudi A. Battery/supercapacitors combination in uninterruptible power supply (UPS). IEEE Trans Power Electron 2013;28:1509–22.
[86] Kollimalla SK, Mishra MK, Narasamma NL. Design and Analysis of Novel Control Strategy for Battery and Supercapacitor Storage System. IEEE Trans Sustain Energy 2014;5:1137–44.
[87] Koohi-Kamali S, Tyagi V, Rahim N, Panwar N, Mokhlis H. Emergence of energy storage technologies as the solution for reliable operation of smart power systems: a review. Renew Sustain Energy Rev 2013;25:135–65.
[88] Nayar CV, Ashari M, Keerthipala W. A grid-interactive photovoltaic uninterruptible power supply system using battery storage and a back up diesel generator. IEEE Trans Energy Convers 2000;15:348–53.
[89] Chauhan A, Saini R. A review on integrated renewable energy system based power generation for stand-alone applications: configurations, storage options, sizing methodologies and control. Renew Sustain Energy Rev 2014;38:99–120.
[90] Chen X, Fu Q, Wang D. Performance analysis of PV grid-connected power conditioning system with UPS. 4th IEEE Conference on Industrial Electronics and Applications, 2009 ICIEA IEEE; 2009. p. 2172-6.
[91] Bortolini M, Gamberi M, Graziani A. Technical and economic design of photovoltaic and battery energy storage system. Energy Convers Manag 2014;86:81–92.
[92] Colak I, Kabalci E, Fulli G, Lazarou S. A survey on the contributions of power electronics to smart grid systems. Renew Sustain Energy Rev 2015;47:562–79.
[93] Farhangi H. The path of the smart grid. Power Energy Mag IEEE 2010;8:18–28.
[94] Fu Q, Montoya LF, Solanki A, Nasiri A, Bhavaraju V, Abdallah T, et al. Microgrid generation capacity design with renewables and energy storage addressing power quality and surety. IEEE Trans Smart Grid 2012;3:2019–27.
[95] Lasseter RH. Smart distribution: Coupled microgrids. Proc IEEE. 2011;99:1074–82.
[96] Zhao B, Song Q, Liu W, Xiao Y. Next-generation multi-functional modular intelligent UPS system for smart grid. IEEE Trans Ind Electron 2013;60:3602–18.
[97] Chiang H, Ma T, Cheng Y, Chang J, Chang W. Design and implementation of a hybrid regenerative power system combining grid–tie and uninterruptible power supply functions. IET Renew power Gen 2010;4:85–99.
[98] Abusara M, Guerrero JM, Sharkh SM. Line-interactive UPS for microgrids. IEEE Trans Ind Electron 2014;61:1292–300.
[99] Xu D, Li H, Zhu Y, Shi K, Hu C. High-surety Microgrid: Super Uninterruptable Power Supply with Multiple Renewable Energy Sources. Electr Power Compon Syst 2015;43:839–53.
[100] Subburaj AS, Pushpakaran BN, Bayne SB. Overview of grid connected renewable energy based battery projects in USA. Renew Sustain Energy Rev 2015;45:219–34.
[101] Khadem SK, Basu M, Conlon M. Parallel operation of inverters and active power filters in distributed generation system—A review. Renew Sustain Energy Rev 2011;15:5155–68.
[102] de Smidt-Destombes KS, van der Heijden MC, van Harten A. On the availability of a k-out-of-N system given limited spares and repair capacity under a condition based maintenance strategy. Reliability Eng Syst Safety 2004;83:287–300.
[103] Raynham MB, Tuttle MR. Redundant power supply and storage system. Google Patents; 1998.
[104] Zhang X, Xue H, Xu Y, Chen H, Tan C. An investigation of an Uninterruptible Power Supply (UPS) based on supercapacitor and liquid nitrogen hybridization system. Energy Convers Manag 2014.
[105] IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications. IEEE Std 446-1995 [The Orange Book]. 1996:1-320.