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Review on Renewable Source Integrated Topologies with Power Quality Enhancing Strategies

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Abstract- New emerging technologies and growing population of present world demands more electrical power. These drastic changes in power demand can be supplied through effective renewable energy source grid integration. As input of these sources is not stable, need to plan for efficient and cost effective models. This paper gives a complete overview of different grid tied renewable source topologies, power quality issues, different control strategies and optimal usage of renewable sources. This review drives the power engineers and researchers towards the renewable source based hybrid topology design with different control strategies where both renewable integration and power quality mitigation together taken care. With this review one can understand the design of efficient and cost effective renewable source integrated grid topologies to cope with modern world abnormal power demand.

Keywords- Renewable energy units; Power quality; Grid integration; Active power filters; Hybrid energy system.

1. Introduction

The primary concern of an efficient grid structure is to provide continuity in power supply to consumers and to protect consumer equipment from abnormalities in power supply[1-2]. This needs a thorough study of topologies for REU's integration to the grid and type of control schemes to be selected for compensating abnormalities in supply[3-6]. This paper provides a basis for understanding REU's, different topologies for integrating REU's to the Grid as well as alleviating abnormalities in the power supplied to load. Paper also describes optimal sizing of renewable integration and various vigorous control strategies for improving the power quality.

In literature many reviews supported renewable integrated topologies with different control strategies. But most of them were confined to one particular area. In [7-8], authors described photovoltaic grid integrated topologies with different control techniques. Similarly wind integration challenges and topologies were presented in [9-10]. The multi functional inverter topologies along with control strategies were well described in [11]. In spite of these current review covers all the possible Renewable source grid integrated topologies with power quality improvement. Ergo, one can decide which topology is best suited for their requirement. The added advantage of this review is that it also presents comparison of wide range of felicitous control techniques, selection criteria for power conditioning devices, Power quality standards. This review brings all the required information under single roof for researchers and designers to congruous design of an efficient topology to satisfy present modern world power needs by considering global warming. Paper is organized as section 2 describes power quality issues, standards and grid synchronization limits. Section 3, explains various Grid Integrated REU topologies with power quality improvement. Section 4, gives clear idea of various control schemas used for power quality improvement. Section 5, helps to select a suitable controller based on their application. It also covers Power management and optimal sizing of REU integrated topologies. Interesting conclusions are drawn in section 6.From this section one can understand different types of renewable sources available and the need for their integration to grid for current world power needs and to cope with increasing global warming.

2. Power Quality

Growing pace of complex power system is more concern about the buzz word of power industry, 'Power Quality'. Non linear loads [12] connected to the system deteriorates power quality, which results a great impact on economic loss. This leads to development of various strategies to mitigate poor Power Quality.

Power Quality [PQ] is well defined as "changes in frequency or voltage or current which causes the malfunctioning and damage to the consumer equipment" [13-15]. Power quality of power system needs deep study of various design issues. The PQ study involves basic concepts & aspects of PQ [16-17], measuring & monitoring of PQ [18-19], Modelling & analysis [20-21] and problem solving [22-24]. In literature PQ issues, detection & classification were studied in [25]. This analysis of PQ events will help researchers and engineers working with power quality. The designers should achieve PQ standards for their optimal topology to provide quality power to the loads. Some of the PQ standards are demonstrated in Table.1.

PQ is widely studied in distribution system, where nonlinear loads and integrated REU's will degrade the PQ [26-27]. The general REU integrated grid system is as shown in Fig.2, where controller is separately connected to the line. To mitigate the PQ disturbances at line, need a thorough study of optimal REU integration to grid, power quality issues and standards, selection of suitable power conditioning devices. Table 2 provides the grid synchronization limits to integrate REU to the grid. PQ problems associated with each Distributed Generation sources are shown in Table 3.

In improving power quality, filters play a paramount role. Exordium stages of power system passive filters were widely in use, which are cost effective and simplest in design. These passive filters suffer with overloading, resonance & excessive harmonic current [28-29]. At the middle stages of power system development, Active Power filters are used to mitigate the PQ problems. These APF's consists of energy storage elements and power electronic devices. APF's provide compensation of harmonics, reactive power demand, voltage variations and neutral currents. The ongoing power system utilizes hybrid filters, which have coalesced advantages of passive filters and active filters [30-32].

As conventional sources suffer with lack of availability & pollution, renewable source integration completely changes modern electric power system structure. Centralized control power system slowly migrates to decentralized control power system[39]. Let us understand the state of art of renewable sources to congruous design an optimal distribution power system. These REU's provide pollution free power and abundantly available in nature. DG integration requirements are given in Table 4.[39]. Let us understand the state of art of renewable sources to congruous design an optimal distribution power system. These REU's provide pollution free power and abundantly available in nature. DG integration requirements are given in Table 4.

This section provides an idea of power quality issues, standards and its importance. Here, DG requirements and its related PQ issues are presented. With this, power system designer will understand which standards have to be considered and attains knowledge about bottlenecks for REU integration.

Table 1. Power quality Standards

IEEE Standard	Inference
IEEE Std. 519-1992 [33]	Defines Limits of Total Harmonic Distortion (THD) ,Voltage and Current Harmonics, Total Demand Distortion (TDD), and Point of Common Coupling (PCC)
IEEE 100 [34]	Electrical Standard definitions dictionary
IEEE Std. 1159-1995[35]	Defines PQ disturbances such as short durations, transient, frequency variations, steady state variation, long duration variation
IEEE Std 1547-2003 [36]	Describes standards for integrating DGs to the power system.
IEEE Std. 1459-2010[37]	Definition for Electrical Power quality measurement under balance, unbalanced, sinusoidal and non- sinusoidal conditions
ISO 50001 [38]	Standards for certifiable Energy Management Systems for energy objectives, energy policies and processes.

Table 2. Limits for synchronization parameters [36]

KVA Rating of DG	ΔF (Hz)	ΔV (%)	ΔØ (o)
0 to 500	0.3	10	20
>500 to 1500	0.2	5	15
>1500 to 10000	0.1	3	10

Table 3. PQ issues Associated with different DG's

PQ Problem	Wind Energy Unit	Solar Energy Unit	Micro/Small Hydro Unit	Diesel Unit
Current Harmonics	✓	✓	✓	
Interruption	✓	✓		
Voltage Flicker	✓	✓		✓
Voltage Harmonics	✓	✓	✓	
Voltage Unbalance		✓		
Voltage sag/Swell	✓		✓	✓

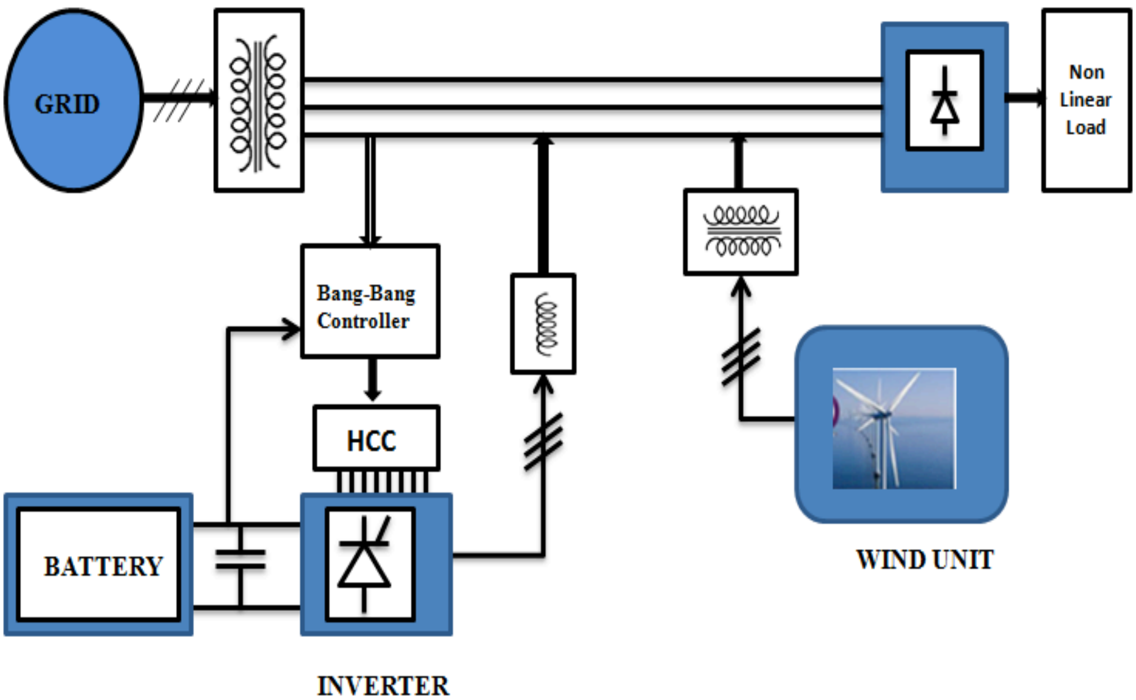


Fig.1. REU connected Traditional topology for Power quality Improvement [40-41]

Table 4. DG integrated Requirements [43].

Requirement	**DG<10KW**	**DG 10-100KW**	**DG 100-1000KW**	**DG>1000KW**
Grounding Impedance	N	N	Optional	Often
Telecommunication	N	Optional	Optional	Y
Dedicated Transformer	Optional	Optional	Y	Y
Special monitoring and control Requirements	N	Optional	Y	Y
Protective Relays	Y	Y	Y	Y

Y : YES N : NO

Table 5. Comparison of different Storage techniques [45-46]

Type	Response Time(ms)	Efficiency (%)	Energy Density(Wh/kg)	Cost($/kWh)
Battery	30	60-80	20-200	150-1300
SMES	5	95-98	30-100	High
Flywheel	5	95	5-50	380-2500
NaS	<100	70	120	450
Super Capacitor	5	95	<50	250-350

3. Grid integrated Topologies

The power quality improvising grid topologies have been adapting continuous changes in their structure for alleviating voltage & current abnormalities, harmonics and reactive power compensation. As the world is more concern about pollution, REU's integration made drastic change in the overall topology structure. For an efficient topology one should go through the detailed topologies available for integrating REU's and at the same time power quality issues has to be mitigated. The exordium stage of topologies uses separate power conditioning devices for power quality improving and REU integration. This utilizes more devices which increases the cost of design. An efficient topology is one which uses common power conditioning devices for both REU integration and power quality improvement.

The exordium stages of Renewable Energy Integrated Grid Topologies (REIGT's), concentrated on direct integration of renewable energy Units to Point of common coupling/line [40-42]. The modern age REIGT's considers optimum usage of Renewable Energy Units, continuity in supply, optimum cost and system power quality improvement with felicitous hybrid control techniques. Energy storage devices plays paramount role in smoothening fluctuated energy integrated to the grid and power quality improvement [44]. Different energy storage techniques used in grid integrated renewable source topologies are well compared in Table 5.

In [47], authors presented a cost effective 3 phase 4 wire REIGT. The model shown in Fig.3 utilizes Solar /Wind energy unit fed simple bang-bang current control techniques based controller. Proposed topology compensates current harmonics, unbalanced currents, Reactive power and neutral current. It also presents model working under diverse power conditions like PREU=0, PREU> PLOAD and PREU< PLOAD. Topology replaces the battery with REU which intern reduces the cost of hardware required. The model is designed in MATLAB/SIMULINK environment and validated with DSP control strategy based laboratory setup.

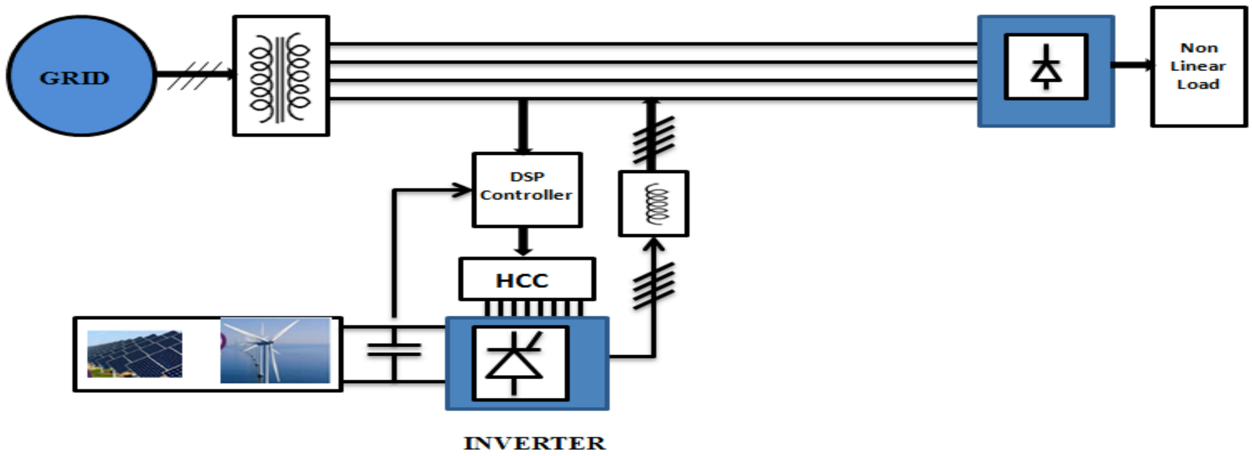
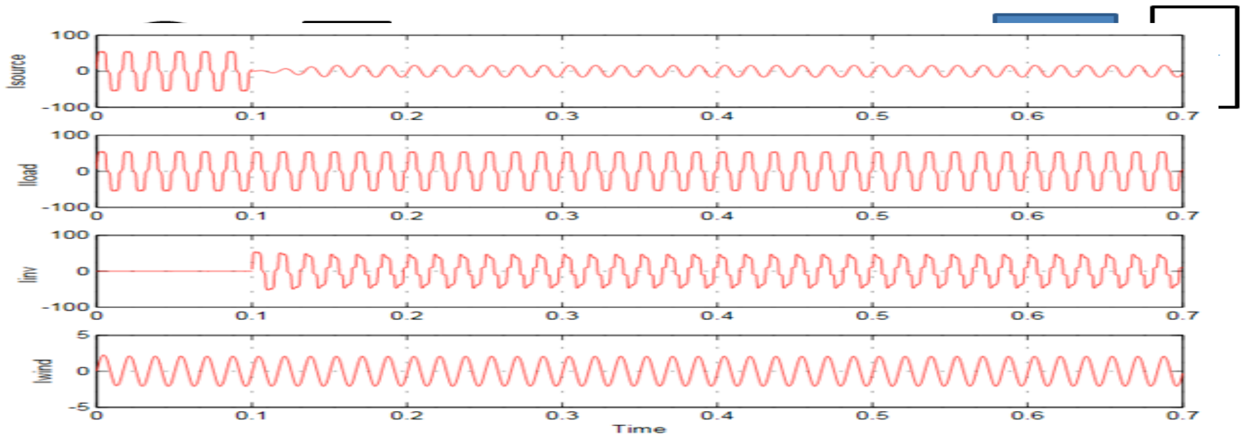


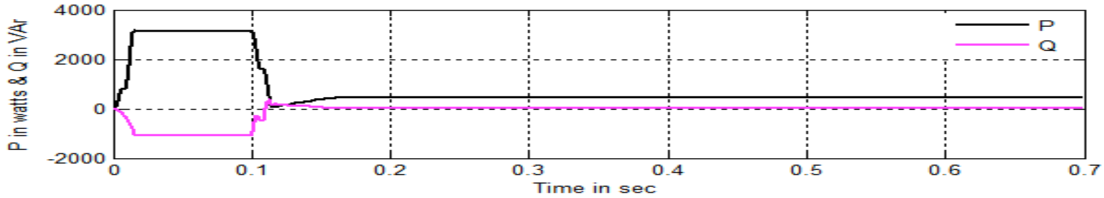
Fig.2. REU supported Shunt Controlled REIGT with Power quality Improvement [47]

In [48], authors demonstrated a continuous compensation of harmonics in throughout the day with effective utilization of solar energy unit. The topology uses a novel I cosΘ control technique [49] for reactive power compensation and current harmonics elimination. Another similar model [50], presents an effective integration of wind energy and solar units to the grid which is shown in Fig.3. Here, Photo Voltaic unit fed controller compensates reactive power required by the load as well as existing wind energy unit. It also reduces the harmonic content in source currents. In [50], authors proven I cosine ANFIS based PV fed Active power filter effectively mitigates the power quality issues and injects real power. Majority of the Power required by Load is provided from PV and wind unit and remaining power is delivered from grid. Obtained Current harmonics are within the Standards of IEEE. Fig.4 clearly presents steady state performance, Power flow and harmonic suppression.

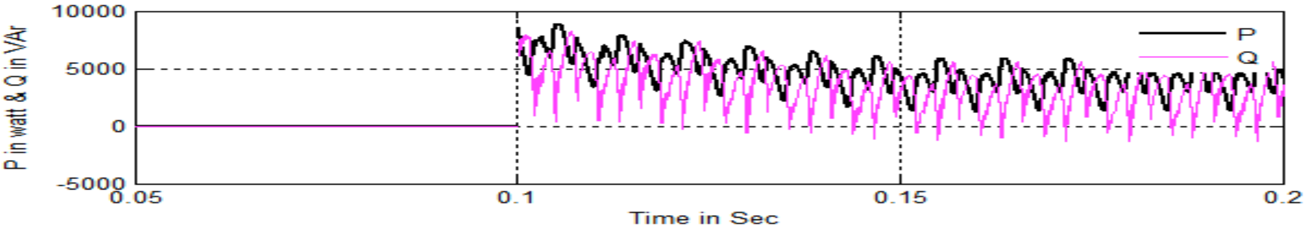
Fig.3. REU supported I Cosine based Shunt Controlled REIGT with PQ Improvement [50]



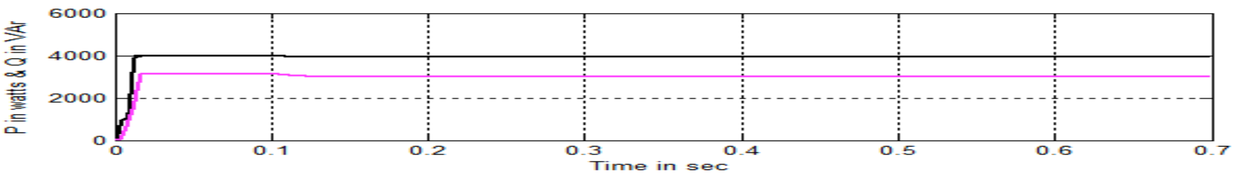
4(a) Source, Load ,Inverter and Wind currents.



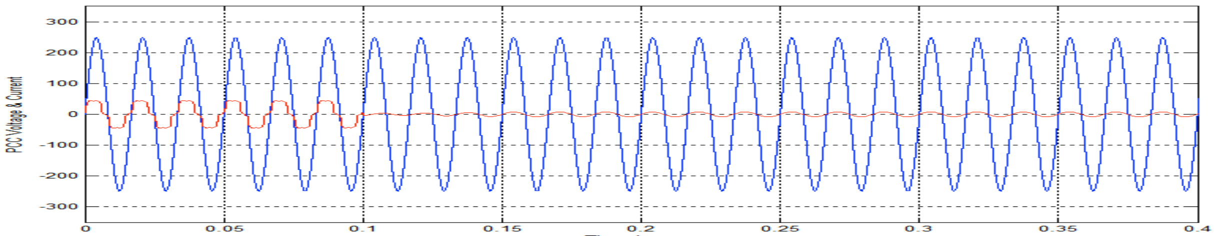
4(b) Source P & Q



4(c)LoadP&Q



4(d) PV fed inverter P & QIJRER



4(e) Unity Power Factor

Fig. 4. Simulated Results Presented in [50]

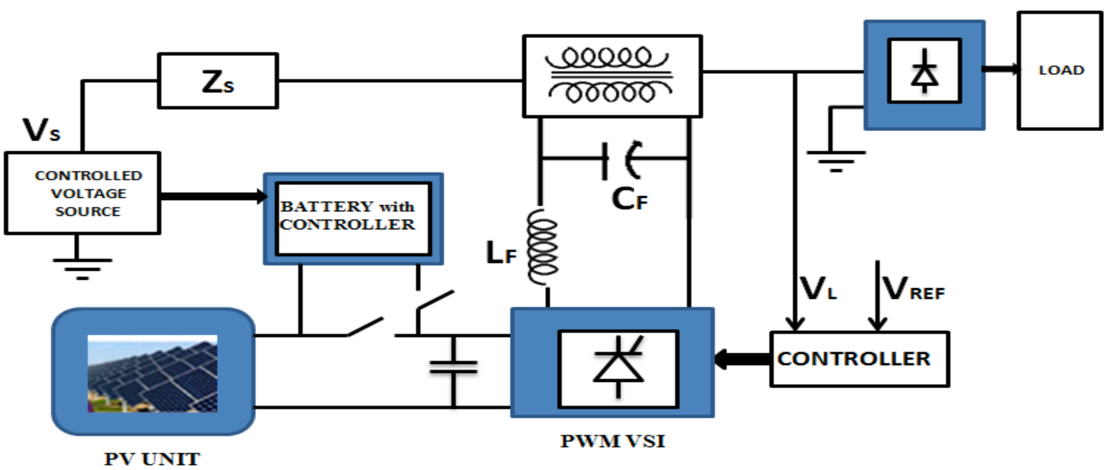


Fig.5. REU supported DVR topology with PQ Improvement [52]

The wind energy unit integrated topology is proposed in [51]. The wind unit considers variable wind speed input with Permanent Magnet Synchronous Generator. An efficient Photo Voltaic Unit fed Dynamic Voltage restorer (DVR) is given by [52] and shown in Fig.5. Here, Photo Voltaic (PV) unit fed DVR compensates Voltage imperfections like sag, swell and interruption throughout the day. A similar model with hybrid control technique is presented in [53]. The model shown in Fig.8 also reduces harmonic content in load voltage. Fig.6 presents the performance of PV fed Z source Inverter (ZSI) based DVR. Voltage imperfections are compensated and load voltage harmonics are suppressed with in IEEE standards. In [54], authors discussed similar kind of model for three phase system. Here, d-q control based DVR effectively deals with voltage harmonics and voltage variations under different fault conditions. Authors proven that this model is cost effective and suppresses the harmonics. The PV unit fed Unified Power Quality Conditioner was proposed [56] to increase overall power quality. The model compensates the voltage sag/swell, reactive power required and Current harmonics in Source current due to non linear loads.

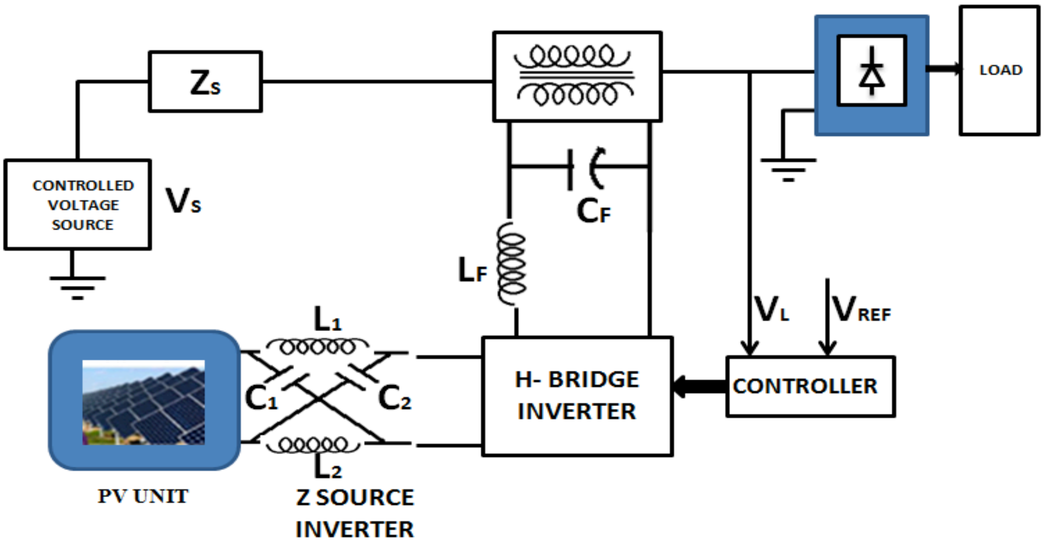


Fig.6. REU supported ZSI based DVR with PQ Improvement [53]

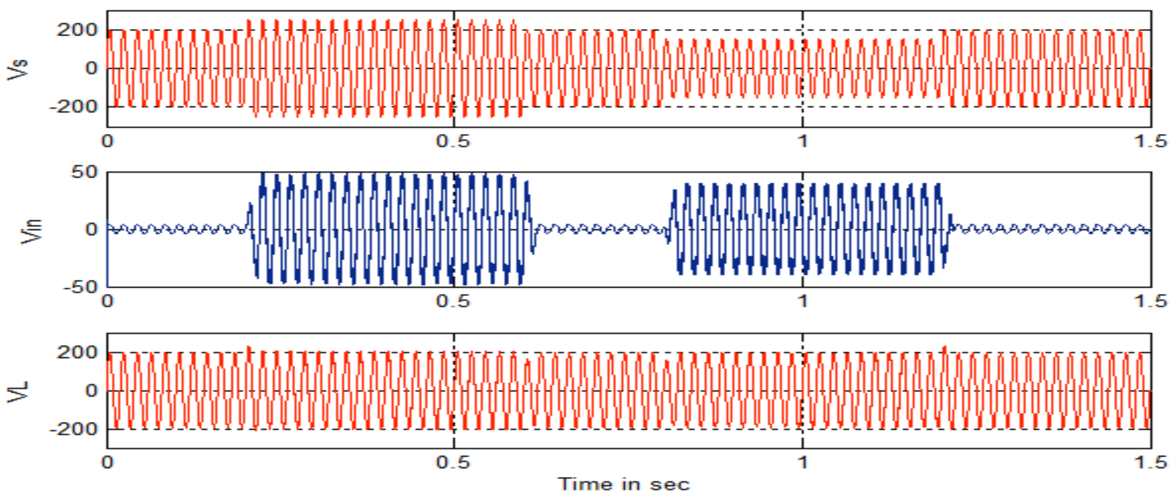


Fig. 7. Source, Load and injected Voltages[53]

The Hybrid topology given in [55] uses both Photo Voltaic and Fuel cell units. Model presents an optimal usage of renewable sources for grid power quality improvement. Here, Fuel cell controls the uncertainties of the PV unit and reduces (MPPT) maximum power point tracking. This model compares the performance with and without Fuel cell. Presented model suppresses the harmonics in source current within IEEE standards. The real power from PV is injected into the line to serve the part of load power. Here, authors succeed to Hybrid topology depicted in [57] presents a novel coordination control mechanism for power transfer at AC and DC links under variable load conditions with different renewable source integration.

Considered hybrid model in Fig. 8. In this model, authors studied hybrid model with Wind and PV integration at AC and DC side. Bidirectional inverters efficiently work for power transfer between both sides. This section covers the main objective of the paper. Here, different topologies considering renewable source integration along with power quality improvement have been described. With REU integration power is delivered to the ad as well as excess power is feeded to grid.

The integrating devices acts like power conditioning for REU and as power quality enhancing devices. With the above study we can conclude that for improving power quality in existing wind integrated system [50], PV and fuel cell coordinated unit [55] fed shunt controller /unified controller [56] achieves the optimal design objective. With this review, authors suggests a Hybrid system [57] with fuel cell supported PV unit at DC side and wind/PV fed UPQC at AC side, model will achieves both power quality improvement and REU integration to the

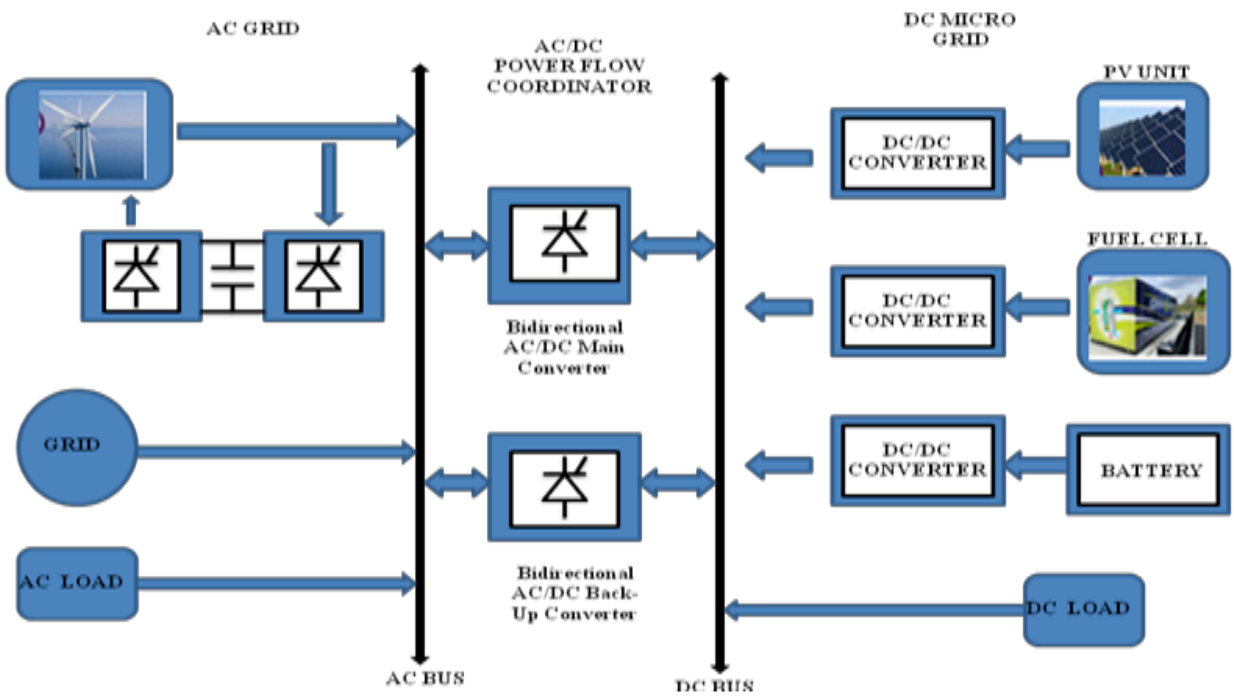


Fig.8 Hybrid REIGT with Power quality Improvement [57]

4. Control Strategies

Before selecting a felicitous control technique, we need to understand Filter devices which are viable solution for power quality improvement. In alleviating PQ issues, passive Filters [58-61] were used for longer period. These passive filters suffer with resonance and fixed compensation. The most viable solution for power quality improving devices is active power filters. Active power filter consists of series, shunt or combination of both inverters. The voltage source inverters are mostly used devices than current source inverters, due to their characteristics and efficiency [62-66]. Active power filters injects equal and opposite distortions to cancel out the disturbances there by improves the power quality at connected common line of the system. The controller gathers information by detecting current/voltage signals using current transformer/voltage transformer, isolation amplifiers and Hall Effect sensors. Using these signals, controller derives compensating signals in terms of current/voltage levels. At last, gated signals are generated by using different techniques like sinusoidal pulse width modulation (SPWM) [67], Hysteresis band current controller [47, 50] and Space Vector pulse width modulation (SVPWM)[68]. As the active filters are costlier, Hybrid Filters [69-71] were introduced, which provides simple design, optimum cost and high reliability. The PQ disturbances can be effectively eliminated by choosing an efficient control strategy. This can be effectively studied by classifying based on control techniques.

4.1. Traditional Control strategies:

These are classified as frequency domain compensation and time domain compensation techniques. Frequency domain control strategies are based on Fourier Transform [72-73]. Here, compensating commands are generated by separating the compensating harmonic components. The online Fourier Transform application results in tortuous computation and more response time. In time domain compensation, many methods are available. They are instantaneous 'p-q' theory [74-76], Synchronous 'd-q' theory [77-79], notch filter method [80-81] and sliding mode controller [82-83].

4.2. Modern Control Strategies:

The Modern control strategies refer to utilization of soft computing techniques in actual control strategy. Such as artificial neural network based controller mitigates reactive power and current harmonic compensation in [50], Particle swarm optimization controller mitigates voltage and current harmonics in [84], Hybrid PSO-ANFIS based controller mitigates voltage sag and reactive power in [85] and genetic algorithm mitigates power fluctuations in [86]. Table 7 gives additional control strategies for PQ improvement with renewable source integration to the grid. Table 8 gives the comparative study of shunt active power filter (SAPF) Control strategies. This section gives the knowledge of different control strategies available for improving power quality. It covers most of the available control strategies. It provides the earlier and modern soft computing based control strategies used to alleviate power quality issues in different topologies. With this section, one can cull felicitous filter combination and efficient control technique to get efficient performance of whole system.

5. Active Power Filter Selection Criteria and Optimal Power management

The Active Power Filter should be selected based on application. Different applications have different requirements such as voltage or current based compensation in single phase, 3Ø 3- wire and 3Ø 4-wire systems. Series active power filters uses voltage based compensation [106-107]. Voltage sag/swell compensation, voltage harmonic reduction, and voltage flicker suppression comes under voltage based compensation. Shunt active power filer uses current based compensation [108-109]. Reactive power compensation, current harmonic suppression, neutral current compensation and load balancing come under current based compensation. The coalesced shunt and series active filters uses both current and voltage compensation [110-111]. This combination has higher rating, cost and size. So, other combinations such as series active power filter with passive shunt filters are preferred. Active power filters are selected based on individual requirements as shown in Table 9.

The optimal design or optimal configuration of Hybrid Integrated system should have lower (NPV) Net Present value [112-113]. For choosing the optimal sizing of the hybrid systems, several techniques were presented in literature such as Genetic Algorithm [114-115], Particle Swarm optimization [116-117], Neural Network [118-119], and Simulated Annealing [120]. With the optimal sizing of Hybrid integrated system, we can achieve technical and economical performance of power delivery and promotes green power source integration. Genetic Algorithm and neural network methods provide efficient performance to attain global minima, but suffers with hard coding and training respectively. In [121], authors presented an optimal power supply and demand management in uncertain REU's integrated grid model. Authors formulated optimum power generation scheduling and power consumption for fuel cost minimization. knowledge and past observations. Later optimization is formulated for the problem selected. Here, a novel two stage algorithm is introduced for optimization. Primarily, the uncertainty of REU is represented with reference distribution based on empirical ANN based hybrid topology with PV/wind units is proposed in [122] for standalone approach to deliver the consumer loads. Several power optimization techniques were proposed for hybrid systems [123-124]. This section provides detailed information to cull congruous type of filters based on requirement. It also presents optimal sizing techniques for REU integrated topologies. This knowledge is the utmost requirement for efficient topology design to achieve cost effective and optimal integration of renewable energy units.

Table 7. Modern control strategies with power quality improvement.

Ref.	Renewable source	Control Method	Inference
[88]	PV	Synchronous reference frame	Reduces the harmonics in voltage and current to 0.5 & 0.7% resp. Maintains the voltage fluctuations within 6%
[89]	PV	P–Q theory	Maintains UPF, Neutral current compensation, Faster response time and improved THD
[90]	PV	Voltage angle control	Compensates the harmonics in current and voltage, Eliminates sag and swell up to 81% and 26%
[41,91]	PV/Wind	ANFIS	Reactive power compensation, current harmonic cancellation, Reduced Electrical cost.
[92]	Wind	Genetic Algorithm	Mitigates power fluctuations Cost efficient
[93]	PV	PSO Fuzzy	Reduces current Harmonics and eliminates voltage sag
[94]	PV	PSO-ANFIS	mitigates Voltage Sag with UPQC minimal real power injection technique

Table 8. Comparison of SAPF Control strategies for power quality improvement.

Control Strategy	Response Time	Complexity	References
Sliding Mode Controller	++	+	[95]
Deadbeat Controller	+	+++	[96-97]
Predictive Controller	++	++	[98]
Negative Sequence Current Controller	++	+	[99]
Repetitive Control	++	+	[100]
One-cycle Control	+++	+	[101]
Hysteresis Current controller	+++	+	[102]
Wavelet Theory	+++	+++	[103]
Fuzzy based Controller	+++	++	[85]
Neural Network Based controller	+++	++	[41]
Genetic Algorithm Based Controller	+++	+++	[104]
Particle Swarm Optimization Based Controller	+++	+++	[105]

Table 9. Filter selection criteria based on requirement.

Compensation for Specific Application	Filters			
	Series Connected Active Filter	Shunt Connected Active Filter	Series Active and Shunt Passive Filter	Shunt and Series connected Active Filter
Load Balancing(LB)		+		
Neutral Current Compensation(NC)		++	+	
Current Harmonics Reduction (CH)		++	+++	+
Reactive Power Compensation(RP)		+++	++	+
Voltage Harmonics Compensation(VH)	+++		++	+
Voltage Regulation(VR)	+++	+	++	+
Voltage Balancing(VB)	+++		++	+
Voltage Sag/Swell(VS)	+++	+	++	+
Voltage Flicker(VF)	++	+++		+
(CH+RP)		+++	++	+
(CH+RP+LB)		++		+
(CH+RP+LB+NC)		+		
(VH+VR)	++			+
(VH+VR+VF+VS)	++			+
(CH+VH)			++	+
(CH+RP+VH+VR)			+	++
(VR+VB)	++		+	
(RP+LB)		+		
(RP+LB+NC)		+		
(CH+RP+VB)		++	+	
(CH+LB)		+		
(CH+NC+VB)		+	++	

+ : Less preferred/Less complexity/Slower response

++ : Medium/Average

+++: Highly preferred/More complex/Faster response

6. Conclusion

This review presents a wide range of renewable energy source integrated topologies with variant vigorous control techniques, which provides a clear understanding for selection of felicitous topology depending on individual requirements. This analysis gives complete knowledge of renewable integrated topologies for researchers, manufacturers, engineers and beginners.The exordium sections conclude that before designing an optimal topology, we should consider pollution free power source selection and standards to be met for fulfilling modern world energy needs. Different types of available renewable sources were highlighted. Later section provides implemented models which optimally integrates renewable sources along with power quality improvement. The final section provides classification of ifferent control strategies and selection criteria of filters for mitigating power quality issues. In addition, optimum sizing and power management techniques precisely discussed. Populated review concludes that one should cull the topology and control technique based on their application. The Hybrid topology with soft computing based control technique gives an optimal solution for power quality improvement with simple design, reliable control action and cost effective. This research review promotes pollution free energy supply with optimal renewable source integration.

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