Comprehensive Review of Distributed FACTS Control Algorithms for Power Quality Enhancement in Utility Grid With Renewable Energy Penetration

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ABSTRACT Rapid industrialization and its automation on the globe demands increased generation of electrical energy with more reliability and quality. Renewable energy (RE) sources are considered as a green form of energy and extensively used as an alternative source of energy for conventional energy sources to meet the increased demand for electrical power. However, these sources, when integrated to the utility grid, pose challenges in maintaining the power quality (PQ) and stability of the power system network. This is due to the unpredictable and variable nature of generation by these sources. The distributed flexible AC transmission system (DFACTS) devices such as distributed static compensator (DSTATCOM) and dynamic voltage restorer (DVR) play an active role in mitigating PQ issues associated with RE penetration. The performance of DFACTS devices is mostly dependent on the type of control algorithms employed for switching of these devices. This paper presents a comprehensive review of various conventional and adaptive algorithms used to control DFACTS devices for improvement of power quality in utility grids with RE penetration. This review intends to provide a summary of the design, experimental hardware, performance and feasibility aspects of these algorithms reported in the literature. More than 170 research publications are critically reviewed, classified, and listed for quick reference for the advantage of engineers and academicians working in this area.

INDEX TERMS Adaptive control algorithm, conventional control algorithm, DFACTS device, modern utility grid, power quality, renewable energy source.

ABBREVIATIONS

| Abbreviation | Description                                      |
|--------------|--------------------------------------------------|
| 3P4W         | Three phase four wire                            |
| 3P3W         | Three phase three wire                           |
| ABT          | Admittance based theory                          |
| ACA          | Adaptive control algorithm                       |
| ADALINE      | Adaptive linear element theory                   |
| ALMS         | Adaptive least mean square                       |
| ANF          | Adaptive notch filter                            |
| ANFIS        | Adaptive neuro-fuzzy inference system            |
| ARLS         | Adaptive recursive least square                  |
| CCA          | Conventional control algorithm                   |
| DFACTS       | Distributed flexible AC transmission system      |
| DSP          | Digital signal processing                        |
| DSSC         | Distributed static synchronous series compensator|
| DSTATCOM     | Distributed static compensator                   |
| DSTC         | Distributed static compensator                   |
| DSSC         | Distributed static series compensator            |
| DSVC         | Distributed static var compensator               |

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I. INTRODUCTION

The increased demand for electrical power, the requirement of environmental conservation and depletion of fossil fuel reserves have forced the utilities to increase the penetration level of RE into the utility grid [1], [2]. Renewable power can reduce power losses, mitigate environmental pollution, defer or eliminate system upgrades, reduce operating costs, and improve voltage profile due to their nature and penetration at distribution level [3]. The share of RES in total primary energy supply would rise from 14% in 2015 to 63% in 2050 [4]. The high penetration level of renewable energy (RE) sources into the utility grid lead to PQ challenges and deteriorate the quality of electrical power significantly [5]. PQ issues associated with the grid integration of RE sources include fluctuations in voltage, reactive power flow, harmonics, excessive neutral current, etc. [6]–[9]. The other important issues associated with RE placement, sizing and voltage ride-through in distribution systems reported in [10], [11]. Research work to resolve the issues of power quality associated with WES, SPV, and FC is investigated using simulation studies [12] and hardware approach [13]. This work further also investigated the enhancement of stability of the utility network in the presence of RE. The development of FACTS devices used in the distribution network to improve the PQ has also resulted in the increased RE penetration levels in the grid [14], [15]. The studies also revealed that PQ mitigation could be achieved using distribution static compensator controlled by synchronous reference frame theory [16]. This is also validated by the use of real-time digital simulation (RTDS). The FACTS devices including, DSTATCOM, DVR, and UPQC were found to be effective in mitigating PQ issues such as harmonics and load unbalancing [17], [18]. These devices also help to maintain voltage regulation [19], [20]. However, the performance of FACTS technologies is largely dependent on the implemented control algorithm [21]. These control algorithms may be conventional and adaptive in nature [22]. The conventional control algorithms are implemented using instantaneous symmetrical component theory (ISCT), instantaneous reactive power theory (IRPT), synchronous reference frame theory (SRFT), etc. [23]–[28]. The SRFT control algorithm is the widely used conventional control method for PQ improvement. The performance of these algorithms is not satisfactory due to the use of the inbuilt phase-locked loop (PLL). An important feature desired in the smart grid control and operation is the fast response of control algorithm. Further, it is also desired that these control algorithms track the changes associated with RE penetration and the dynamics of the loads accurately. These can not be
TABLE 1. Symptoms, causes, impacts and solution of PQ disturbances in 3P3W and 3P4W utility network [1]-[65].

| PQ Disturbances | Details |
|-----------------|---------|
| Voltage sag or dip | Description: Sags in the RMS voltage level decreases between 10-90% of nominal voltage for 1-3 cycles or longer. Symptoms: Loss of voltage, flickers, sudden device shutdown, decreased equipment lifetime, and flickering lights. Causes: Issues on the 3P3W or 3P4W utility system, start-up of large loads, inductive leading and switching on the large loads. Impacts: Malfunction of electronic-based equipment, equipment damage, dropouts, and maloperation of sensitive equipment. Solution: DVI, DVS, static transfer switch. |
| Very short Intermittents | Description: Complete loss of electrical supply for a few milliseconds to 1 second. Symptoms: Decreased equipment life and flickering lights. Causes: Automatic opening and closing of protection devices of 3P3W and 3P4W utility network and life of sensitive equipment. Impacts: Tripping of sensitive equipment and electromechanical relay and malfunctioning. Solution: Machine-Generator set, DISSC, DVS, static transfer switch. |
| Long Intermittents | Description: Complete loss of electrical supply for a duration greater than 1.5 sec. Symptoms: Loss of supply to customers and computer shutdown. Causes: Equipment failure, trees, vehicles striking to lines or poles, failure of protection devices and circuit breakers tripping. Impacts: Equipment shutdown and sudden damaging occurred in sensitive equipment. Solution: DVI, VPIQ, Machine-Generator set, DISSC. |
| Voltage spikes | Description: Abnormal rise or fall of the voltage for a short duration ranging from several microseconds to few milliseconds. Symptoms: Flicking lights, data loss and interference. Causes: Lightning, arcing, overvoltages, and switch faults. Impacts: Destruction of electronic components, tripping of sensitive equipment, damage to insulation and winding. Solution: DISSC, DISETCOM, DVR, VPIQ. |
| Voltage swell | Description: The RMS voltage level increases to 115%–118.5% of normal voltage, at the power frequency for durations of 5 cycles to 1 minute. Symptoms: Momentary loss and data errors, equipment shutdown, decreased equipment life and flickering lights. Causes: Switches ON and switch OFF heavy loads, transients regulation is altered during off-peak hours. Impacts: Loss of efficiency in rotating machines. Solution: DISSC, DISETCOM, DVR, VPIQ. |
| Electronic Distortion | Description: Deviation of various sine waves from distorted waveform with different phase, magnitudes and multiples of power frequency. Symptoms: Electrical equipment malfunctioning, decreased performance of the equipment, improper operation of systems. Causes: Arc furnaces, welding machines, weak AC grid, non-linear loads, integration of renewable energy sources and rectifiers. Impacts: Increase neutral current, nuisance tripping of thermal protection, mal-operation of sensitive equipment, overheating. Solution: Active and passive filters, multi-point connection. |
| Voltage fluctuation | Description: Voltage oscillations with magnitudes of a few percent at 50-60 Hz. Symptoms: Power equipment/machinery overloaded, the decreased performance of the equipment, improper operation of systems. Causes: AC drives, unbalanced loads, overcurrent, harmonic current components, welding and arc furnaces. Impacts: Mal-operation of lighting,oots and unbalanced loads. Solution: DISSC, DISETCOM, DVR, VPIQ. |
| Voltage Unbalance | Description: Deviation in voltage magnitudes with varying phase angle. Symptoms: Overloading of equipment, reduced efficiency and speed variation in motors. Causes: Large 1-phase loads cause due to the capacitors load, traction load, unbalanced loads and location of grid-based utilities. Impacts: 3-phase induction machines, overheating in motors and life of the equipment. Solution: DISSC, DISETCOM, DVR, VPIQ. |
| Over voltage | Description: A condition in which the voltage value exceed the rated voltage limit. Symptoms: Dim or bright lights, equipment shut down, over heating of equipment and reduced efficiency. Causes: Unbalanced and pulsed load switching, capacitor switching and current voltage regulation. Impacts: Overheating in motors, mal-operation of sensitive equipment, relay and life of the equipment. Solution: DISSC, DISETCOM, DVR, VPIQ. |
| Power frequency Variation | Description: Any deviation in the fundamental frequency. Symptoms: Dim or bright lights, hearing, reduced efficiency and motor run down. Causes: Usually caused by failure of the generator, extreme loading conditions. Impacts: Loss based systems, slow and massive power failure in the grid. Solution: DISSC, DISETCOM, DVR, VPIQ. |
| Under voltage | Description: A condition in which the voltage reduces below the rated value of the power system equipments. Symptoms: Dim or bright lights, equipment shut down, reduced efficiency, distortion and malfunctioning. Causes: Heavy network loading, loss of generation, power factor variation, lack of VAR support. Impacts: All equipment without backup supply facility shut down in this condition. Solution: DISSC, DISETCOM, DVR, VPIQ. |

Achieved efficiently by the use of conventional control methods. Hence, the researchers have focused on the development of adaptive algorithms for the control of smart utility grid, which might provide an effective solution for PQ and stability challenges. These algorithms also provide the possibility of high RE penetration level of in the 3P3W and the 3P4W utility grid. These algorithms include Adaline, ALMS, and ARLS based algorithms [29]–[34]. These algorithm functions using the principle of continuously updating the weight component according to the system data. The attractive features of these algorithms include simple architecture, simplified calculation and fast convergence with a negligible steady-state error. These control algorithms have been successfully validated in the hardware framework using R&D controllers such as DSP, FPGA and dSPACE [35], [36].

This paper presents a comprehensive focused on the performance of algorithms used for the control of DFACTS devices to improve power quality in 3P3W and 3P4W utility grid with RE penetration, which were validated with hardware framework. More than 170 research publications [1-176] have been reviewed critically and presented in seven sections of this paper. Section 1 in the introduction and introduces the general aspects of power quality and DFACTS devices. Section 2 covers power quality issues and international guidelines for their mitigation. Section 3 presents the use of DFACTS devices in the area of PQ improvement in utility grid with RE penetration. Experimental implementation of DFACTS devices in 3P3W and 3P4W utility grid with RE penetration is described in Section 4. Section 5 details the principles and block diagrams of various control algorithms used for the DFACTS. Key findings and recommendation for future research work are presented in Sections 6. Finally, the conclusions are drawn in Section 7.

II. POWER QUALITY

In the healthy grid, power quality is referred to the level of customer satisfaction in terms of uninterrupted power supply and maintaining voltage, current and frequency within the permissible limits defined in grid codes [37]. The deviation of these quantities from the permissible range might result in malfunction and failure of utility and consumer equipment. RE penetration into the utility grid would further deteriorate the quality of power due to the unpredictable output of the RE sources and converters used for their interfacing with the grid [38], [39]. Hence, IEEE has led down the guidelines in terms of PQ, which is computed based on voltage fluctuations, flickers, and frequency distortion in the utility grid with RE penetration [40]. These limit the penetration.
level of RE sources into the distribution grid. Therefore, PQ mitigation is a major concern for electric smart grids [41]. The commonly observed PQ disturbances, their symptoms, causes of these disturbances, their impacts on equipment and possible mitigation approaches are detailed in Table 1. The data included in Table 1, are selected from the books and research articles cited in this review paper. Further, appropriate PQ mitigation techniques are discussed in this Table. This will help the readers to select the appropriate DFACTS device for mitigation of a specific PQ disturbance. Also, the possible alternate solutions for PQ mitigation is also included in this Table which would give the basic idea for minimization of the PQ disturbances. This would be helpful when DFACTS devices are not present in the system.

### A. INTERNATIONAL STANDARDS OF POWER QUALITY

International bodies such as Institute of Electrical and Electronics Engineers (IEEE), European Committee for Electrotechnical Standardization (CENELEC) and International Electrotechnical Commission (IEC) are continuously coordinating with each other to standardize the PQ at grid level [42]. These organizations provide various international standards on PQ, which help to regulate the PQ with and without RE penetration. The guidelines for power loss analysis with SPV penetration proposed in [43]. The IEEE standard 519-1992 helps to understand harmonics in power system network [44], [45]. IEEE-P1547 standard states that voltage fluctuations must be less than ±5% and the amount of DC content must be less than 0.5% of total output current at the PCC [46]. The harmonics voltage and current limits for different voltage levels are updated in IEEE standard 519-2014 [47]. This updated standard significantly focused on harmonic measurements and introduced the statistical evaluation in brief and short time-harmonic measurements. It can be perceived from IEEE standard 519-2014, that the voltage distortion level decreases with an increase in voltage level and current harmonics limits depend on the short circuit strength of the system. The relevant IEEE standards related to PQ and RE penetration into the utility grid are presented in Table 2.

### III. DFACTS DEVICES

The DFATCS devices are the flexible AC transmission system (FACTS) devices used in the distribution grid to control line impedance, phase angle, current harmonics, voltage harmonics, voltage magnitude and unbalance loading to maintain power quality. In [49], [50], a new concept of DFACTS is recommended, which is a promising economical solution to PQDs in a utility grid-tied with RE sources. It also provides many advantages as they are small in size, less in cost, and easy for implementation compared to conventional FACTS devices. They are found to be effective in the control of phase angle and line impedance [51], [52]. The DFACTS devices are efficient in the enhancement of PQ in the utility grid with RE penetration [53]. Performance comparison of DFACTS devices for PQ improvement has been presented in Table 3. Performance of the DFACTS devices for PQ mitigation will depend on the different attributes which are included and discussed in this Table. These attributes of DFACTS devices are beneficial to evaluate performance level in hardware design.

The main advantages of DFACTS for PQ improvement in the utility grid with RE penetration as follows [54],

- Enhanced utilization of existing utility grid.
- Increased flexibility and power flow control in a utility grid with RE penetration.
- Enhancement of transient and dynamic stability limit of the utility grid.
- Increased system reliability and security.
- Environmental friendly.
- Increased quality of power supply.

The details related to various DFACTS devices are also provided in the below subsection.
A. TYPES OF DFACS DEVICES

The DFACS devices can be classified into series-connected, shunt connected, shunt-series connected, and series-series connected based on interconnection with utility grid as shown in Fig 1.

1) SERIES DFACS DEVICES

These compensators are connected in series with the utility grid. They may have mutable impedance like a capacitor and reactor. Series compensators work on the principle of injecting voltage in series with grid voltage thereby controlling the real power flow in the utility network. This minimizes real and reactive power loss in the distribution network [55], [56]. These devices can also be utilized to limit the short circuit current, eliminating the subsynchronous resonance (SSR) and damping power oscillations [57]. Commonly used series-connected DFACS devices include DSSC, DSSSC, DVR etc.

2) SHUNT DFACS DEVICES

A shunt compensator is a VSC connected in parallel with the utility grid [58]. It may have mutable impedance and source. Shunt compensators work on the principle of injecting current in shunt with grid voltage, thereby allowing power flows by enhancing the voltage profile in the utility network. These devices help in maintaining power factor, balancing the load, mitigating reactive power, reducing harmonics, and providing uninterrupted power [56], [59]. Commonly used shunt connected DFACS devices include DSTATCOM, DSVC, etc.

3) SHUNT-SERIES DFACS DEVICES

This compensator provides both shunt and series compensation. These are controlled in a co-equal manner using series and shunt elements. In this compensator, shunt component of the compensator inject current, and the series component of the compensator injects voltage in the utility grid. The active and reactive power exchange between these compensators through the dc-link capacitor presented in [60]. These are found to be effective in improving system stability and mitigating PQ issues with RE penetration [61], [62]. Various shunt-series DFACS devices include UPQC, DTCSC, etc.

4) SERIES-SERIES DFACS DEVICES

Interline power quality compensator (IPQC) is widely used active and reactive power compensator in utility grid-tied with RE sources. It consists of two branches (inductive and capacitive), which help to control active and reactive power independently by adjusting the phase shifter or branch impedance. The IPQC can regulate power flow in both the direction and minimizes short circuit current, to allow active power flow control in utility network [60], [63]. Combined DFACS devices have considerable flexibility and hence are more complex and difficult to control.

IV. HARDWARE ARCHITECTURES OF MODERN UTILITY GRID

Block diagram of the new utility network with sensitive load, power quality mitigation device and RE sources at PCC is illustrated in Fig 2. Wind Energy source and Solar-PV have been considered as a renewable energy source, which is connected at the point of common coupling (PCC) through grid side converter (GSC) with the conventional generator. These grid side converters are also termed as DFACS devices and controlled with appropriate control algorithms. These algorithms are helping to increase the output efficiency of the RE sources. The sensitive loads also connected at PCC, which is considered as a distribution load.

The RE penetration with digital control of DFACS devices is the main feature of the modern utility grid [64] and requirements for updating and modifying the benchmarks for modern grids are detailed in [65]. The modern architecture of the utility grid can be classified into modern three-phase three-wire (3P3W) and three-phase four-wire (3P4W). The modern 3P3W utility system is employed for balanced three-phase loads, i.e., induction motor load. The major challenge associated with this system includes lack of return path for unbalanced currents which would lead to the unbalanced supply voltage. The architecture of the modern 3P4W utility grid also provides a choice of connecting single-phase loads. In the case of unbalance, neutral wire provides a path for neutral current circulation. The major challenges associated with the modern grid include excessive neutral current, harmonics, and voltage regulation. DFACS devices help to mitigate power quality issues and allow high RE penetration in modern utility grids. Feasibility of different topologies of modern utility grids, based on their performance, with various RE sources, are provided in Table 4. It has been perceived from Table 4 that, one type of RE source integrated with 3P3W or 3P4W utility network is feasible and involves less computational complexity in both the RES side and grid side.
controls. However, complexity will be increased when hybrid RE penetration (two or more types of RE sources) is available. This is observed due to the requirement of synchronized control for all converters in the presence of hybrid RE sources. Hence, there is the trade-off between single and hybrid RE sources in the utility grid. On the one hand, the single RE source in the utility grid has better performance than the hybrid RE sources in terms of less complexity, and on other hands, the output power performance of hybrid RE penetration would be the better option for meeting load demands.

A. MODERN 3P3W UTILITY GRID

The experimental architecture for RE sources integrated to 3P3W utility grid with DFACTS device is depicted in Fig 3. The modern 3P3W utility grid is realized from a 50Hz three-phase AC grid with RE source (ETS600 X 17DPVF) supplying power to the nonlinear/sensitive loads. Meanwhile, power quality is improved by DFACTS (SKM50GB123) device. The switching signals are provided by control algorithm via dSPACE 1103 or 1104. The voltage and current signals are sensed by LEM LV-25P and LEM LA-55P hall-effect based sensors. The optical isolation is provided by optocoupler 6N136. In 3P3W utility grid, the neutral conductor of the load and fourth leg of DFACTS device is connected through the neutral wire. This highlighted fourth wire (neutral wire) would help to provide more clarity and difference between Experimental architecture for RE penetration into 3P3W and 3P4W utility grid with DFACTS. The modern 3P4W utility grid realized using a 50Hz three-phase AC grid with RE source (ETS600 X 17DPVF) supplying power to the nonlinear load. Meanwhile, power quality is improved by DFACTS (SKM100GB128DN) device. The control algorithm provides the switching signals via dSPACE 1202 micro lab box. ABB-EM10BB and EL50P1BB hall-effect based sensors sense the voltage and current signals. The optical isolation is provided by optocoupler 6N136. In 3P4W utility grid, the neutral conductor of the load and fourth leg of DFACTS device is connected through the neutral wire. This fourth leg of DFACTS device, with coupling inductor, is also utilized for compensation of excessive neutral current. The 3P4W hardware framework reported in the literature includes the design of an SPV system with four-leg DSTATCOM [81], [82]. The self-excited induction generator with adaptive stator current compensator for voltage and speed control is presented in [83]. The single-stage SPV with DSTATCOM is used in [84] for power quality improvement under unbalanced loads. Shunt Active Power Filter (SAPF) for mitigating the neutral-point oscillation has been presented in [85]. A 4-leg DSTATCOM has been employed to limit fault current [86], to compensate the neutral current [87], mitigate unbalanced load variations [88] and excessive neutral current [89], [90]. These investigations demonstrated the multi-functional capabilities of DFACTS devices with RE penetration in the 3P4W utility system.

As a conclusion of section IV, the performance of modern utility grid in terms of PQ mitigation largely depends on the type of load, RES, strength of AC grid and power quality mitigation methodology (selection of DFACTS device and its control algorithm) [53]. The significant difference of selection of DFACTS devices and its control algorithms for 3P3W and 3P4W modern utility grid is highlighted below:

- The 3P3W modern utility grid requires 3-leg Insulated Gate Bipolar Transistor (IGBT) switch, which is based on the specific application (i.e. shunt compensation or series compensation).
- The 3P4W modern utility grid requires fourth-leg of IGBT based thyristor for alleviating the neutral current.
- To control the fourth transistor of the 3P4W modern utility grid extra PWM is required which is generated by the control algorithm by using fourth wire of the system. The control algorithm computes extra PWM for fourth-leg of the switch by comparing sensed (actual) neutral current signal and reference neutral current signal. The recommended features of these algorithms include robustness, speed and adaption to the system changes based on the current information related to load and RE sources.
V. THE EXISTING CONTROL ALGORITHMS

Various control algorithms, proposed to estimate reference signals, which in turn used to control DFACTS devices are broadly classified into two categories, namely frequency-domain (FD) and time-domain (TD) algorithms. The performance of these algorithms is graded based on how fast and accurate reference signals are generated. The frequency-domain based algorithms include recursive discrete Fourier transform (DFT), fast Fourier transform (FFT) and miscellaneous FD based algorithms. These algorithms for power quality mitigation studies are not often used due to their inaccuracy, as reported in [91]. The TD based control algorithms found to be suitable for power quality mitigation [92]. These algorithms are sub-classified into conventional and adaptive control algorithms. The existing conventional control algorithm (CCA) are based on Clark transformation of voltage and current signals. Adaptive control algorithm (ACA) are based on error minimization and weight updation of voltage and current signals. Fig 4 presents the general classification of various control algorithms.

A. CONVENTIONAL CONTROL ALGORITHMS

Conventional control algorithms work on the concept of 3-phase to 2-phase and 2-phase to 3-phase transformation of voltage and current signals with phase-locked loop circuit for the estimation of reference gate signals required to drive the DFACTS devices [93]. The design process involved for designing of conventional control algorithm is explain in below subsection.

1) DESIGN OF CONVENTIONAL CONTROL ALGORITHM

Various steps involved in designing of conventional control algorithms are detailed below. Standard notation and nomenclature are used based on the research articles cited in this review.

- Estimation of in-phase and quadrature unit templates: The ac terminal voltage $v_t$ is determine using the three-phase source/grid voltages ($v_{sa}$, $v_{sb}$, $v_{sc}$) as,

$$v_t = \sqrt{2/3(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}$$ (1)

Three-phase in-phase (active) unit vector templates ($u_{pa}$, $u_{pb}$, $u_{pc}$) can be written as,

$$u_{pa} = v_{sa}/v_t, \quad u_{pb} = v_{sb}/v_t, \quad u_{pc} = v_{sc}/v_t$$ (2)

Three-phase quadrature (reactive) unit templates ($u_{qa}$, $u_{qb}$, $u_{qc}$), can be written as,

$$\left\{ \begin{align*}
    u_{qa} &= -u_{pb}/\sqrt{3} + u_{pc}/\sqrt{3} \\
    u_{qb} &= \sqrt{3}u_{pa}/2 + (u_{pb} - u_{pc})/2\sqrt{3} \\
    u_{qc} &= -\sqrt{3}u_{pa}/2 + (u_{pb} - u_{pc})/2\sqrt{3}
\end{align*} \right.$$ (3)
• **Estimation of Loss components:** PI voltage regulator is used to generate active and reactive loss components. Reactive loss component ($i_{qr}(n)$) is utilized to maintain terminal voltage at PCC, this is derived from PI voltage regulator.

$$i_{qr}(n) = i_{qr}(n - 1) + k_{pq}(v_{te}(n) - v_{te}(n - 1)) + k_{iq}v_{te}(n)$$  \(4\)

where, $i_{qr}(n - 1)$ and $v_{te}(n - 1)$ are preceding value of reactive loss component and voltage error. The current value of this voltage error ($v_{te}(n)$) is calculated as,

$$v_{te}(n) = v_m(n) - v_t(n)$$  \(5\)

where, $v_m$ represents the peak amplitude of phase voltage and taken as reference value of terminal voltage ($v_t$). PI voltage regulator maintains the dc bus voltage by calculating active loss component ($i_{dr}(n)$).

$$i_{dr}(n) = i_{dr}(n - 1) + k_{pd}(v_{de}(n) - v_{de}(n - 1)) + k_{id}v_{de}(n)$$  \(6\)

where, $i_{dr}(n - 1)$ and $v_{de}(n - 1)$ are the preceding value of active loss component and dc voltage error. However, the current value of this dc voltage error is,

$$v_{de}(n) = v^*_{dc}(n) - v_{dc}(n)$$  \(7\)

where, $v^*_{dc}$: reference DC bus voltage calculated as $(v^*_{dc} = 2\sqrt{2}v_{LL}/\sqrt{3}m)$. $v_{LL}$ represents voltage (line to line) at PCC, $m$ is modulation index. $v_{dc}$: actual DC link voltage.

• **Extraction of fundamental component of load currents:** The computation of active and reactive component of load current depends on 3-phase to 2-phase and 2-phase to 3-phase conversion methodology used in the control algorithms.

• **Generation of three-phase reference signals:** The extracted in-phase and quadrature load currents obtained using PLL circuit are corrected with the help of voltage unit templates to derive active and reactive components of grid current signals. These components are combined to generate reference grid signals using 2-phase to 3-phase conversion. The details of the reference current generation signals may vary with the type of algorithm.

• **Generation of gating signals:** The generated 3-phase reference signals ($i^*_{abc}$) along with actual grid signals ($i_{abc}$) are fed to pulse width modulation based controller to generate gating signals for DFACTS devices.

Note: The gating signals for the fourth leg switches of DFACTS device in 3P4W utility grid are calculated from the current error signal by comparing sensed neutral signal ($i_{sn}$) and reference neutral signal ($i^*_{sn}$). These signals are calculated as,

$$i_{sn} = -(i_{sa} + i_{sb} + i_{sc})$$

### FIGURE 4. General classification of control algorithms.

![Diagram of control algorithms](image)

### FIGURE 5. Basic building block of general hardware framework of a control algorithm for DFACTS devices.

- High speed computer
- FPGA based or DSPACE based R&D controller
- Opto coupler
- Signal conditioning unit
- Amplification driver
- Hall effect based sensors
- Switching signals for DFACTS device

- Vgabc, Igabc, Vlabc, Vdc, RES, RES, Vdc
The implementation of the generalized approach of conventional control has been implemented in various conventional control algorithms as detailed in following subsections.

2) INSTANTANEOUS REACTIVE POWER (IRPT) CONTROL THEORY

The concept of IRPT was first proposed by H. Akagi and has been used for generation of the reference signal for DFACTS devices to mitigate PQ issues. The basic working methodology of this theory includes the transformation (3-phase to 2-phase) and reverse transformation (2-phase to 3-phase) of voltage and current quantities for the estimation of reference current signal. The computations involved in the IRPT theory to estimate instantaneous active (p) and reactive (q) components of current signals have been presented in [94].

The basic building block of IRPT is depicted in Fig 6. The 3-phase voltage ($V_{sabc}$) and load currents ($i_{labc}$) are converted in to $\alpha$-$\beta$-0 components using Clark transformation and zero sequence component of active power is suppressed. The loss component ($i_{loss}$) is estimated using the PI regulator. This loss component is combined to average (dc) part of the instantaneous reactive power ($\overline{q}$) for estimating ($P_{loss}$). This component and average (dc) part of the instantaneous reactive power ($\overline{q}$) are combined to calculate $i_\alpha$ and $i_\beta$ current signals. These signals in-turn are utilized to generate reference current signals with the help of reverse Clark’s transformation. These reference signals and actual grid signals are fed to the HCC to generate gating signals for DFACTS device.

\[
\begin{bmatrix}
    i_{sa}^* \\
    i_{sb}^* \\
    i_{sc}^*
\end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix}
    1/\sqrt{2} & 1 & 0 \\
    1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\
    1/\sqrt{2} & -1/2 & -\sqrt{3}/2
\end{bmatrix} \times \begin{bmatrix}
    i_{sa} \\
    i_{sb} \\
    i_{sc}
\end{bmatrix}
\]  

where, $i_{sa}^*$: zero sequence component and it is zero in 3P3W utility grid, $P$: average (dc) part of the instantaneous power, $i_{sa}^*$ and $i_{sb}^*$: reference grid signals, $\Delta = v_\alpha^2 + v_\beta^2$, $\alpha$ and $\beta$: orthogonal coordinates,

\[
\begin{bmatrix}
    i_\alpha \\
    i_\beta
\end{bmatrix} = 1/\Delta \begin{bmatrix}
    v_\alpha - v_\beta \\
    v_\beta - v_\alpha
\end{bmatrix} \times \begin{bmatrix}
    P \\
    0
\end{bmatrix}
\]  

3) INDIRECT CURRENT CONTROL THEORY

The basic building block of ICCT is illustrated in Fig 7. In ICCT control theory, 3-phase grid voltages are utilized for the computation of 3-phase reference currents. These reference currents consist of in-phase component (active component) and out-phase component (quadrature component) as presented in [95], [96]. The active reference current ($i_{smd}^*$) component is kept constant. This constant depends on the unit vector templates ($u_{sabc}$) and active power required by the load. This unit template is multiplied by reference current ($i_{smd}^*$) to obtain reference active component of current ($i_{sabcq}$). The PI controller provides quadrature component of the reference current signal ($i_{smq}^*$) by comparing terminal voltage ($v_{t}$) with its reference voltage ($v_{dc}^*$). This current signal is multiplied by quadrature template ($w_{sabc}$) to obtain reference quadrature component of current ($i_{sabcq}$). Both the ($i_{sabcq}$) and ($i_{sabcq}$) component of currents are combined to generate reference current signals ($i_{sabc}$). The estimated reference current signals are compared with actual 3-phase grid signals ($i_{sabc}$) to generate gating signals for DFACTS device.

\[
i_{sabcq} = i_{smd}^* \times u_{sabc}
\]  

4) SYNCHRONOUS REFERENCE FRAME CONTROL THEORY

SRFT control theory is based on the sensed load current and grid voltage signals [97]–[99]. The basic building block of SRFT is illustrated in Fig 8. The 3-phase current signals have been converted into $\alpha$-$\beta$-0 axes using Clark transformation. This frame is further transformed in to d-q-0 frame to obtain direct-axis ($i_d$) and quadrature-axis ($i_q$) current components. These d-q components are filtered with the help of LPF to obtain ($i_{ddec}$) and ($i_{qdqc}$) components. The reference direct axis current ($i_{dde}^*$) is generated by adding filtered direct axis component ($i_{ddec}$) with direct axis loss component ($i_{dloss}$). This ($i_{dloss}$) loss component is perceived by comparing dc link voltage ($v_{dc}$) with its reference voltage ($v_{dc}^*$) using DC proportional integral controller. The quadrature axis ($i_{qdqc}$)
component is computed by subtracting filtered quadrature 
($i_{qdc}$) component and quadrature axis loss component ($i_{qloss}$). This $i_{qloss}$ component is obtained by comparing terminal voltage ($v_i$) with its reference voltage ($v_i^*$) using an PI controller. Finally, the reference signals in a–b–c frame are obtained by reverse Park’s and Clark’s transformation using PLL. The estimated reference signals are compared with actual 3-phase grid voltages. These unit templates and load currents are combined to generate instantaneous active and reactive current components. This p–q templates are filtered by low pass filter with appropriate frequency to obtain active ($P$) and reactive ($Q$) components.

The active unit template ($u_{abc}$) is computed by subtracting filtered quadrature ($i_{qdc}$) component and quadrature axis loss component ($i_{qloss}$) component is obtained by comparing terminal voltage ($v_i$) to compute ($Q_{dc}$) component of grid current to compute ($Q_r$) component of dc current. Further, this component is divided by the constant value computed using terminal voltage ($v_i$) to obtain reference susceptance ($B_{qf}$). These computed signals help to obtain fundamental active ($i_{abcp}$) and quadrature ($i_{abcq}$) current components. Both signals are combined to obtain reference grid current signals. The estimated reference signals are compared with actual 3-phase grid signals ($i_{abc}$) to generate gating signals for DFACTS device.

$$i_{abcp} = G_{pt} \times v_i \times u_{abc} \quad \text{(15)}$$

$$i_{abcq} = B_{qf} \times v_i \times w_{abc} \quad \text{(16)}$$

where,

$$G_{pt} = P_r / (v_i^2 (3/2)) \quad \text{(17)}$$

$$B_{qf} = Q_r / (v_i^2 (3/2)) \quad \text{(18)}$$

6) MISCELLANEOUS CONVENTIONAL CONTROL ALGORITHM

Apart from the algorithms mentioned in the above section, the other conventional control algorithms have played an important role in PQ mitigation with DFACTS devices. These includes, power balance control [101], instantaneous symmetrical components control [102], sliding mode control (SMC) [103], average unit power factor control [104], voltage template and PI controller [105], PLL based control [106] and their modified methods. However, the experimental framework for conventional control algorithms has not been extensively used with RE penetration in the utility grid.

It has been reported that the compatibility and performance of conventional control algorithms with RE penetration are not providing good results as expected. Hence, the performance of these algorithms is low compared to adaptive control algorithms due to limitations as described in Table 5. The conventional control algorithms use complex circuitry like PLL, 3-phase to 2-phase conversion blocks, 2-phase to 3-phase conversion blocks. Therefore computational complexity associated with these algorithms is high and dynamic response is found be slow. Hence, the performance of conventional control algorithms is poor in mitigating the harmonics. However, when these algorithms are born in the hardware-based R&D controllers like DSP, the oscillations are found to be high in computational speed and DC link voltage.
TABLE 5. Limitations of conventional control algorithms.

| S.No. | Limitations |
|-------|-------------|
| 1.    | Complex circuitry like PLL is required. |
| 2.    | High computation the dynamic response is slow and more complex. |
| 3.    | DC link voltage and DSS speed oscillations are high. |
| 4.    | Accuracy is medium due to poor stability. |
| 5.    | THD calculation is not accurate due to low dynamic response. |

B. ADAPTIVE CONTROL ALGORITHMS

To enhance the power quality of grid integrated RE sources with DFACTS devices, researchers have started switching to adaptive signal processing-based algorithms. These control algorithms work on continuous updating of weight component of current and voltage signals based on the initial values, old estimation and system changes for the estimation of reference gate signals. The simplest algorithm presented in literature is based on the Least Mean Square (LMS). This algorithm was proposed by Widrow et al. [107]. The notability of the LMS algorithm is easy for implementation. The implementation of neural network-based LMS controlled VSC for PQ mitigation has been presented in [108], [109]. This algorithm is also used in mobile communication [110], [111]. However, this LMS algorithm becomes unstable where the signal to noise ratio (SNR) is low. LMF, which is fourth-order error correction algorithm exhibits stability even with low SNR values [112] as static error and mean square error associated with LMF control is lower compared to LMS algorithm [113]. The LMS/F algorithms found to be classical methods for adaptive system identification (ASI) [114]. The details of the implementation of the recursive least-squares algorithm are presented in [115]. This adaptive algorithm provides better convergence and highly correlated input signals compared to the LMS algorithm. The price to pay for this is an increase in computational complexity. Variable forgetting factor recursive least-squares (VFFRLS) algorithm has been developed in [116], [117]. This algorithm has reduced computational complexity and ability to adopt various changes in the system to obtain desired signals for solving complexity and stability issues [118], [119].

1) DESIGN OF ADAPTIVE CONTROL ALGORITHM

The various design steps involved in adaptive control algorithms are detailed below. Standard notation and nomenclature are used based on the research articles cited in this review.

- **Estimation of active and reactive unit templates:** 3-phase line voltages \(v_{ab}, v_{bc}\) are utilized to obtain phase voltages using the following relation,

\[
\begin{align*}
    v_{sa} &= \frac{2v_{ab} + v_{bd}}{3} \\
    v_{sb} &= \frac{-v_{ab} + v_{bd}}{3} \\
    v_{sc} &= \frac{-v_{ab} - 2v_{bd}}{3}
\end{align*}
\]  

(19)

Peak amplitude of terminal voltage \(v_t\) is given as,

\[
v_t = \sqrt{2/3(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}
\]  

(20)

Three-phase in-phase (active) unit vector templates \((u_{pa}, u_{pb}, u_{pc})\) are given as,

\[
u_{pa} = \frac{v_{sa}}{v_t}, \quad u_{pb} = \frac{v_{sb}}{v_t}, \quad u_{pc} = \frac{v_{sc}}{v_t}
\]

(21)

Three-phase quadrature (reactive) unit templates \((u_{qa}, u_{qb}, u_{qc})\) are given as,

\[
\begin{align*}
    u_{qa} &= -u_{pb}/\sqrt{3} + u_{pc}/\sqrt{3} \\
    u_{qb} &= \frac{\sqrt{3}u_{pa}}{2} + \frac{u_{pb} - u_{pc}}{2}/\sqrt{3} \\
    u_{qc} &= -\sqrt{3}u_{pa}/2 + (u_{pb} - u_{pc})/2/\sqrt{3}
\end{align*}
\]  

(22)

- **Estimation of loss components:** PI voltage regulator is used to generate the active and reactive loss components. Reactive loss component \((W_{eq})\) is utilized to maintain terminal voltage at PCC.

\[
W_{eq}(n + 1) = W_{eq}(n) + k_p(v_{te}(n + 1) - v_{te}(n)) + k_q(v_{te}(n + 1)
\]

(23)

where, \(W_{eq}(n + 1)\) and \(v_{te}(n + 1)\) are updated reactive loss component and voltage error. The current value of this voltage error is computed as,

\[
v_{te}(n) = v_{tn}(n) - v_t(n)
\]

(24)

This regulator maintains dc link voltage by generating active loss component \((W_{cp})\).

\[
W_{cp}(n + 1) = W_{cp}(n) + k_p(v_{te}(n + 1) - v_{te}(n)) + k_d v_{dc}(n + 1)
\]

(25)

where, \(W_{cp}(n + 1)\) and \(v_{dc}(n + 1)\) are the updated active loss component and dc voltage error. The current value of this dc voltage error is,

\[
v_{dc}(n) = v_{dc}^*(n) - v_{dc}(n)
\]

(26)

where, \(v_{dc}^*\): reference DC bus voltage calculated as \((v_{dc}^* = 2\sqrt{2}v_{LL}/\sqrt{3}m)\). \(v_{LL}\) represents voltage (line to line) at PCC, \(m\) is modulation index. \(v_{dc}\): actual DC link voltage. Note: In case of RE penetration \(v_{dc}^*\) perceived from the maximum power point tracking (MPPT) based algorithm. However, output of these algorithms depends on the type of RE sources.

- **Estimation of feed forward term:** The feed forward term \((W_{RES})\) is computed based on current output power \((P_{RES})\) of RES given by,

\[
W_{RES}(n) = 2P_{RES}(n)/3v_t
\]

(27)

- **Extraction of fundamental weight component of load current:** The extraction of active and reactive weight component of load current depends on weight updation methodology used in the control algorithms. Let, the basic load current equation of AC distribution network is given as,

\[
i_L(t) = I_s\sin(wt + \phi) + \sum I_n\sin(nwt + \phi_n)
\]

(28)

It can also be represented as,

\[
i_L(t) = i(t) + i_b(t) = i_p(t) + i_q(t) + i_b(t)
\]

(29)
where, \(i(t)\) is the fundamental current component which is made up of active current \(i_p(t)\) and reactive current \(i_q(t)\) whereas \(i_h(t)\) is the harmonic current components. The initial estimation of the active, reactive part of load current and harmonic parts of load current for a single-phase is given as,

\[
\begin{align*}
    i_p(t) &= W_p \times u_p, \quad i_q(t) = W_q \times u_q \quad (30) \\
    i_h(t) &= i_L(t) - i_p(t) - i_q(t) \quad (31)
\end{align*}
\]

The weights \((W_p)\) and \((W_q)\) are not constant values, and continuously update according to the changes associated with system. Active unit voltage template \((u_p)\) and reactive unit voltage template \((u_q)\) are calculated using grid voltages.

- **Estimation of total active and reactive weight components:** The total active weight component \((W_{sp})\) is calculated by adding dc loss component \((W_{cp})\) to average active weight component \((W_{Lpa})\) and deducting the feed-forward RES weight component \((W_{RES})\),

\[
W_{sp} = W_{Lpa} + W_{cp} - W_{RES} \quad (32)
\]

where,

\[
W_{Lpa} = (W_{qa} + W_{qb} + W_{qc})/3 \quad (33)
\]

Similarly, the total reactive weight component \((W_{sq})\) is calculated by subtracting the average reactive weight component \((W_{Lqa})\) to the ac loss component \((W_{cq})\),

\[
W_{sq} = W_{cq} - W_{Lqa} \quad (34)
\]

where,

\[
W_{Lqa} = (W_{qa} + W_{qb} + W_{qc})/3 \quad (35)
\]

- **Generation of three-phase reference signals:** The active reference signal \((i_{pabc}^*)\) is estimated using total active weight component \((W_{sp})\) and 3-phase active unit templates.

\[
(i_{pabc}^*) = W_{sp} \times u_{pabc} \quad (36)
\]

Similarly, the reactive reference signal \((i_{qabc}^*)\) is estimated using reactive weight component \((W_{sq})\) and 3-phase active unit templates.

\[
(i_{qabc}^*) = W_{sq} \times u_{qabc} \quad (37)
\]

Thus, 3-phase reference grid current signals are generated by combining active reference signal \((i_{pabc}^*)\) and reactive reference signal \((i_{qabc}^*)\).

\[
(i_{abc}) = i_{pabc}^* + i_{qabc}^* \quad (38)
\]

Note: The details of the reference current generation may vary with the type of algorithm.

- **Generation of gating signals:** The generated 3-phase reference signals \((i_{abc}^*)\) along with actual grid signals \((i_{abc})\) are fed to pulse width modulation based controller to generate gating signals for DFACTS devices.

Note: The gating signals for the fourth leg switches of DFACTS device in 3P4W utility grid are calculated from the current error signal by comparing sensed neutral signal \((i_{sn})\) and reference neutral current signal \((i_{n}^*)\). These current signals are calculated as,

\[
\begin{cases}
    i_{n}^* = 0 \\
    i_{sn} = -(i_{sa} + i_{sb} + i_{sc})
\end{cases} \quad (39)
\]

The implementation of the generalized approach of adaptive control has been implemented in various adaptive control algorithms with RE penetration as detailed in following subsections.

2) **ADAPTIVE LINEAR ELEMENT (ADALINE) CONTROL THEORY**

The basic building block of ADALINE control theory is illustrated in Fig 10. The extraction of in-phase component of the load current signals is carried out using NN based LMS algorithm known as ADALINE theory. This control algorithm tracks and estimates the in-phase unit templates \((u_{pabc})\) using 3-phase grid voltages, so as to maintain minimum error. The unit templates and initial weight components are corrected with the help of 3-phase load currents to estimate current error \((e_{pabc})\). These initial weights are initialized randomly. The weights are continuously updated until least mean square error is obtained \([31, 120, 121]\) The weights are updated using following equation,

\[
W_{pabc}(n+1) = W_{pabc}(n) + \mu e_{pabc} \times u_{pabc}(n) \quad (40)
\]

\[
e_{pabc}(n) = i_{Labc}(n) - W_{pabc}(n) \times u_{pabc}(n) \quad (41)
\]
The new weight component is updated by adding the product of the current error component and unit vector component along with adaptive constant ($\mu$). This adaptive constant is kept between the range [0-1] to obtain desired results [122], [123]. The updated weights are averaged to eliminate the effect of unbalancing in the current components. The PI controller provides in-phase component ($I_p$) by comparing dc-link voltage ($v_{dc}$) with its reference voltage ($v_{r}^{pabc}$). This in-phase component ($I_p$) and averaged weight ($W_p$) components are added to obtain updated weight components ($W_p$).

The 3-phase reference signals are generated using updated weight $W_{sp}$ component and in-phase unit templates [30]. The estimated reference signals are compared with actual 3-phase grid signals to generate gating signals for DFACTS device.

3) ADAPTIVE LEAST MEAN SQUARE (ALMS) CONTROL ALGORITHM

The basic building block of adaptive least mean square (ALMS) control algorithm is illustrated in Fig. 11. This algorithm computes fundamental active (p) and reactive (q) weight components of load currents considering the grid voltages and RE source generation [113], [124], [125]. This control algorithm, the new reactive weight component is updated by adding the product of reactive current error component ($e_{qabc}(n)$) and reactive voltage unit vector component along with adaptive constant ($\tau_q$). These updated reactive weights ($W_{qabc}$) are averaged to eliminate the effect of unbalancing in the reactive current components. These averaged weight components are passed through LPF with appropriate frequency to perceive average fundamental reactive weight component ($W_{Lqa}$). This ($W_{Lqa}$) component is deducted from reactive loss component ($W_{qabc}$), which is the output of a PI controller processing voltage error to obtain reactive weight component ($W_{sq}$). This reactive weight component ($W_{sq}$) and reactive unit templates ($u_{qabc}$) are combined to generate 3-phase reactive reference currents ($i_{qabc}$).

$$W_{qabc}(n+1) = W_{qabc}(n) + \tau_q \times u_{qabc}(n) \times e_{qabc}(n)$$

$$e_{qabc}(n) = i_{Lqabc}(n) - u_{qabc}(n) \times W_{qabc}(n)$$

$$i_{qabc}^s = W_{sq} \times u_{qabc}$$

Similarly, the new active weight component is updated by adding the product of active current error component ($e_{pabc}(n)$) and active voltage unit vector component along with adaptive constant ($\tau_p$). These updated active weights ($W_{pabc}$) are averaged to eliminate the effect of unbalancing in the active current components. These averaged weight components passed through the LPF to suppress ripples for obtaining average fundamental active weight component ($W_{Lpa}$). The total active weight component ($W_{sp}$) of grid currents are evaluated by combining the dc loss component ($W_{cp}$) to average fundamental active weight component ($W_{Lpa}$) and the feed-forward RE sources ($W_{RES}$) weights. The active loss component ($W_{cp}$) is obtained using PI controller by comparing DC link voltage with its reference voltage ($v_{dc}^{r}$). This reference value of DC link voltage is computed using RES current and voltages. The feed-forward term of RE sources ($W_{RES}$) is obtained by combining the output power of RE sources ($P_{RES}$) and terminal voltage ($V_t$). This computed active weight component ($W_{sp}$) and active voltage unit templates ($u_{pabc}$) are combined to generate 3-phase active reference currents ($i_{pabc}^s$).

$$W_{pabc}(n+1) = W_{pabc}(n) + \tau_p \times u_{pabc}(n) \times e_{pabc}(n)$$

$$e_{pabc}(n) = i_{Lpabc}(n) - u_{pabc}(n) \times W_{pabc}(n)$$

$$i_{pabc}^s = W_{sp} \times u_{pabc}$$

Both 3-phase reactive reference current ($i_{qabc}^s$) and active reference current ($i_{pabc}^s$) signals are added to obtain reference grid current signals. The estimated reference current signals are compared with actual 3-phase grid current signals to generate gating signals for DFACTS device [67], [126].

$$i_{sabc}^r = i_{pabc}^s + i_{qabc}^s$$

4) ADAPTIVE RECURSIVE LEAST SQUARE CONTROL ALGORITHM

The basic building block of adaptive recursive least square (ARLS) control algorithm is illustrated in Fig. 11 with blue color coding. This algorithm computes fundamental active (p) and reactive (q) weight components of load currents considering the grid voltages and RE source generation [116]. The cost function $j(n)$ is expressed as,

$$Costfunctionj(n) = \sum_{k=1}^{n} \eta(n)e^2(n)$$

where, $n$ is represented as variable length of observed data, $\eta_n(n)$ is weighting factor and $e(n)$ is error component. Likewise, Kalman gain is estimated using following equation,

$$k(n) = [P(n-1)u(n)]/[\lambda + u^T(n)P(n-1)u(n)]$$

$$P(n) = 1/\lambda [P(n-1) - k(n)u^T(n)P(n-1)]$$

FIGURE 11. Basic building block of ALMS and ARLS algorithms.
where, Kalman gain \(k(n)\), inverse of input signal correlation matrix \(P(n)\) and input unit template vector \(u(n)\). The learning of the algorithm is based on the forgetting factor \((\lambda)\). The tracking capability and convergence rate of ARLS depends on forgetting factor \((FF)\) [127]. This FF lies between 0 to 1 [128], [129]. Low value of FF provides better tracking capability and slow convergence rate and high value of FF (near to 1) provides low tracking capability and fast convergence rate.

In this control algorithm, the new reactive weight component is updated by adding the product of reactive current error component \((e_{qabc}(n))\) and reactive Kalman gain \((K_q(n))\) component. These updated weights \((W_{qabc})\) are averaged to eliminate the effect of unbalancing in the reactive current components. This averaged weight components passed through low pass filter to perceived average fundamental reactive weight component \((W_{Lqa})\). This \((W_{Lqa})\) component is deducted from reactive loss component \((cq)\) .

\[ W_{qabc}(n + 1) = W_{qabc}(n) + k_q(n) \times e_{qabc}(n) \]  
\[ e_{qabc}(n) = i_{qabc}(n) - W_{qabc} \times u_{qabc}(n) \]  
\[ i_{qabc}^* = W_{Lqa} \times u_{qabc} \]  

Similarly, the new active weight component is updated by adding the product of active current error component \((e_{pabc}(n))\) and active Kalman gain \((K_p(n))\) component. These updated weights \((W_{pabc})\) are averaged to eliminate the effect of unbalancing in the active current components. This averaged weight components passed through the LPF to suppress ripples for obtaining average fundamental active weight component \((W_{Lpa})\). The total active weight component \((W_{pabc})\) of grid currents combining from the dc loss component \((W_{dp})\) to average fundamental active weight component \((W_{Lpa})\) and the feed forward RE source \((W_{RES})\) weights. The active loss component \((W_{dp})\) is obtained using PI controller by comparing DC link voltage \((v_{dc})\) with its reference voltage \((v_{dc}^*)\). This \((v_{dc}^*)\) voltage is computed using RES current and voltages. The feed forward term of RE sources \((W_{RES})\) is obtained by combining output power of RE sources \((P_{RES})\) and terminal voltage \((v_t)\). This computed active weight component \((W_{pabc})\) and active voltage unit templates \((u_{pabc})\) are combined to generate 3-phase active reference currents \((i_{pabc}^*)\).

\[ W_{pabc}(n + 1) = W_{pabc}(n) + k_p(n) \times e_{pabc}(n) \]  
\[ e_{pabc}(n) = i_{pabc}(n) - W_{pabc} \times u_{pabc}(n) \]  
\[ i_{pabc}^* = W_{sp} \times u_{pabc} \]

Both 3-phase reactive reference current \((i_{qabc}^*)\) and active reference current \((i_{pabc}^*)\) signals are added to obtain reference grid current signals. The estimated reference signals are compared with actual 3-phase grid signals to generate gating signals for DFACTS device.

\[ i_{qabc}^* = i_{pabc}^* + i_{qabc}^* \]  

5) MISCELLANEOUS ADAPTIVE CONTROL ALGORITHMS
Apart from the algorithms mentioned in above section, the other adaptive signal processing based control algorithms have played an important role in PQ mitigation in association with DFACTS devices in utility grids integrated with RE sources. These includes, Filtered-X LMS algorithm [159], adaptive notch filter based multipurpose technique [131], [150], Back-Propagation control control [147], adaptive filter [148], modified synchronous detection [149], kernel incremental meta-learning algorithm [151], adaptive linear optimal filter [160], empirical mode decomposition [153], adaptive learning-based anti-Hebbian [146], noise cancellation [161], adaptive notch filter (ANF) [157], automatic synchronization control control [162], ANFIS based control [163], proportional resonant integral (PRI) controller [164], optimized reactive power compensation algorithm (RPCA) [165], adaptive observer-based harmonic cancellation technique [130], non-linear adaptive controller [166], anti-windup [167], damped second order generalized integrator (DSOGI) [168], [169], decoupled adaptive noise detection (DAND) [170], admittance LMS neural network [126], LMF algorithm [171], combined LMS-LMF [172], momentum least mean square (MLMS) [173], improved linear sinusoidal tracer (ILST) [174], [175] and modified RLS [128]. These algorithms for DFACTS devices have been established successfully and validated by hardware framework.

State of the art, clearly establishes that adaptive signal processing based control algorithms provide ease for estimation of the active component and reactive component along with the less computational complexity. These algorithms exhibit robustness and faster response. The performance of various conventional and adaptive control algorithms has been analyzed by selecting various parameters of these algorithms used in recent research as listed in Table 6. However, Table 7 shows the experimental data-based performance analysis of these algorithms. In Table 7, parameters have been selected based on the laboratory-based experimental data from the respective references. It has been perceived from the tabled data that, the implementation of adaptive control algorithms

| TABLE 11. Feasibility and economic consideration of grid tied RES. |
|------------------|------------------|
| Factor           | Clarification    |
| Grid integration | There is no requirement of large-capacity batteries in grid tied RES with DFACTS systems. For similar loads grid-tied system use smaller RES compared to stand-alone systems. |
| Distance to utility network | Grid-tied RES with DFACTS systems should be integrated into utility grid as nearest as possible to avoid unnecessary operations. Stand-alone systems have a big issue, as it is located far from electrical utility networks, which is uneconomical. Distance is increasing losses are also, increases with the length of the line. |
| Balance of system components | International safety standards and regulations may require for new balance of 3PW and 3PW utility system. Initial costs for installation are depending on the balance of system components. |
| Installation cost | Per watt basis, large scale grid-tied RES with DFACTS systems tend to be economical. Grid-tied RES with DFACTS systems endow lower initial cost with the energy costs for heavy loads. |
| Maintenance | There are no moving parts in small scale grid-tied RES with DFACTS systems, so notable maintenance costs is zero percent. |
| Energy use and cost | Energy use is a crucial factor in deciding system size. Reducing energy consumption due to small RES with DFACTS systems greatly reduces the initial capital cost investment. |

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has been found comfortable with R&D controllers and output of these algorithms is superior compared to the conventional control algorithms. In addition to the above, the compatibility and performance of adaptive control algorithms with RE penetration provide better results compared to conventional control algorithms. The performance comparison of 3P3W and 3P4W system in an isolated mode, utility grid-connected mode and RE integrated mode is listed in Table 8 and Table 9. The aim of these tables is incorporating recent research in the area of PQ mitigation. For this purpose, tabulated data shows the system parameters, reference signal generation algorithms, voltage regulation devices, comparators for PWM generator, DFACTS devices used for the various researches in different applications. The performance of various control algorithms has also been discussed in the above mentioned Tables. Based rigorous state-of-the-art included in the revised version of the paper, critical factors which are important for future modern utility grid with RE penetration in terms of feasibility and economic considerations. These factors and their illustrations are presented in Table 11.

**VI. LEARNING OUTCOMES AND RECOMMENDATION FOR FUTURE RESEARCH**

The learning outcomes and recommendation for future research are as follows:
TABLE 9. Performance analysis of 3P3W and 3P4W utility grid with grid connected mode.

| Performances                              | System          | REGA | Regime     | Control   | DFACTS devices | Ref. |
|-------------------------------------------|-----------------|------|------------|-----------|----------------|-----|
| Reactive power compensation and current harmonics have been mitigated. Also, the balancing of asymmetrical loads has been achieved and control of voltage harmonic mitigated. | 3P3W - 100V (L-L), 50Hz, L=5.0 Lf, 3Mf, 0.75f | PI | HCC | Hybrid power flow | [143] |
| Voltage regulation, reactive power and current harmonics have been mitigated. Also, it provides quick response and zero phase shifts along with reducing the computational complexity and cost of the DSTATCOM have been achieved under N-L loads. | 3P4W - 150V (L-L), 50Hz, L=5.0 Lf, 3Mf, 0.75f | PI | PW | DSTATCOM | [144] |
| DC voltage and power losses are generated when active power is generated by inverter, and for this, an LCL filter is introduced. | 3P3W - 100V (L-L), 50Hz, L=5.0 Lf, 3Mf, 0.75f | PI | PW | DSTATCOM | [145] |
| Capacitor of the desired amount of reactive power, and mitigation of harmonics has been achieved under N-L load. | 3P3W - 4 kAh, 41V, L=5.0 Lf, 50Hz | PI | PW | DSTATCOM | [146] |
| Grid voltage has been maintained using earthed neutral line (ENL) | 3P3W - 150V (L-L), 50Hz, L=5.0 Lf, 3Mf, 0.75f | PI | PW | DSTATCOM | [147] |
| Reactive power compensation and current harmonics have been mitigated. Also, the balancing of loads has been achieved under N-L loads. | 3P3W - 150V (L-L), 50Hz, L=5.0 Lf, 3Mf, 0.75f | PI | PW | DSTATCOM | [148] |
| Current harmonics have been mitigated with the maintaining UPV. Also, voltage regulation has been achieved under N-L load. | 3P3W - 150V (L-L), 50Hz, L=5.0 Lf, 3Mf, 0.75f | PI | PW | DSTATCOM | [149] |
| Capacitor of the desired amount of reactive power, and mitigation of harmonics has been achieved under N-L load. | 3P3W - 4 kAh, 41V, L=5.0 Lf, 50Hz | PI | PW | DSTATCOM | [150] |
| Reactive power compensation and current harmonics have been mitigated using Adaptive synchronously rotating (ASR). Also, balancing of loads and voltage regulation has been achieved under N-L load. | 3P3W - 150V (L-L), 50Hz, L=5.0 Lf, 3Mf, 0.75f | PI | PW | DSTATCOM | [151] |
| Power quality has been maintained using earthed neutral line (ENL) | 3P3W - 150V (L-L), 50Hz, L=5.0 Lf, 3Mf, 0.75f | PI | PW | DSTATCOM | [152] |

A wide scope for future research in the PQ mitigation with RE penetration may include:

- A thorough investigation is required of various PQ issues in a utility grid with hybrid RE penetration of different combinations and levels.
- The performance of various adaptive control algorithms of RE sources with variations in the AC grid can be a potential future research topic.
- The investigation into the aspects of sustainability, reliability, cost, size, the weight of various DFACTS devices used for PQ mitigation into the utility grid with RE penetration may be considered as a future research topic.

VII. CONCLUSION

A comprehensive state of the art for different implemented control algorithms to enhance the power quality in 3P3W and 3P4W utility grid with RE penetration has been critically reviewed. The international research status with the details related to design aspects of various control algorithms both in simulation and experimental studies have been presented. The performance of various algorithms is summarized for

- This review provides various concepts related to power quality and its standards in the area of RE penetration into the utility grid, which is useful for grid operators.
- This review provides the performance comparison of various DFACTS devices used to mitigate PQ in utility grids integrated with different RE sources. It also established that potential choice for the PQ mitigation under various conditions is DSTATCOM.
- This review also guides in selecting PQ mitigation method, DFACTS device based on the type of RE penetration and type of the AC grid.
- The beginners of this research area would have exposure to experimental architecture for RE penetration into 3P3W and 3P4W utility grid and DFACTS for PQ improvement.
- This review provides a broad classification of various control algorithms used for PQ mitigation based on conventional and adaptive control methodologies.
- It provides an insight into various aspects of a hardware implementation for control algorithms using different technologies such as FPGA, dSPACE.
guidance. The research beginners in this area would be able to select the topology and control algorithm based on the grid configuration. The technical details of the hardware used for experimental work are also provided in the view of benefiting the designers and researchers in the field of PQ mitigation in the utility grid with RE penetration. A learning outcome of this review and the possible scope of future work have been highlighted. Authors hope that this review will pave the way for new ideas in the implementation of PQ mitigation algorithms in association with DFACTS devices thereby enhancing the RE penetration level for promotion of the green energy.

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