1 Introduction

1.1 PROBLEM STATEMENT

The requirements to reduce greenhouse gas emissions and environmental pollution have motivated the utilities to enhance Renewable Energy (RE) penetration level into the AC grid to meet the increased electrical power demand [Ellabban *et al.*, 2014]. Therefore the share of RE in total primary energy supply is anticipated to rise from 14% in 2015 to 63% in 2050 [IRENA, 2019]. The present global scenarios of renewable and non-renewable sources are presented in Fig. 1.1. The estimated global share of traditional electrical power is 72.7 %, and non-conventional electric power is 27.3 %. Wind Energy (WE) sources have become emerging as mainstream power specialists and as it generates more cost-effective electric power than coal-fired conventional power plants. The installed global wind power capacity has exceeded 60 GW with extensive participation of Induction Generator (IG) based WE sources [Murdock *et al.*, 2020]. Together with custom power devices, these sources promise quantum improvement in expense, performance capability, power quality, and reliability. The WE sources have been considered the most leading sources of power generation by 2050 because they help to minimize the capital expenses for the generation of renewable power and meet the load demand in metropolitan and rural areas [Blaabjerg and Ma, 2013, 2017]. These growths can pave the way for a modern WE power generation revolution for the rural areas. Integrating these sources into the rural (weak) grid decreases the household's peak load demand and provides more economical energy costs to benefit the consumer.

The general difference between urban grid (i.e. stiff) and rural grid (i.e. weak) is, short-circuit ratio at the point of common coupling (PCC), where the grid condition is referred to $SCR \leq 3$. The rural grid is generally located in remote or hilly areas. Due to the large distances from the central grid, the line's impedance increases, and the short circuit ratio (SCR) decreases. Thus, the grid's strength is degraded, and it can be termed as the weak grid, or rural grid [Brekken and Mohan, 2007]. Wind Energy sources are vital for full-fill those conditions by providing continuous day-night electric power without any specific energy storage device. These sources also accommodate grid flexibility, decreases costs, and deliver technical advantages due to co-localization. However, the penetration levels are limited due to power quality (PQ) issues owing to intermittency and uncertainty associated with WE. Penetration levels further aggravate in the presence of non-linear (NL) loads and decrease in SCR of the grid. Despite these issues, the utilities have ambitious goals of penetration levels due to the advantages such as reduction in losses, carbon emission, and running cost. For example, European Union has set a goal of 32% of total RE by 2030 [IRENA, 2019].

Most WE sources employ Induction Generators (IG) to convert wind energy to electrical energy. These are connected to ac grid through a built-in converter. IGs need reactive power support for their successful operation, which is provided by the built-in converter, generally controlled by the conventional vector control schemes. It also helps in mitigating the PQ disturbances associated with WE (intermittency and uncertainty) [Shafiullah, GM and Oo, Amanullah MT and Ali, ABM Shawkat and Wolfs, Peter, 2013]. Mitigation of PQ issues like voltage stability, harmonics, and flickers by built-in converter with vector control scheme has been reported in [Kaddah *et al.*, 2016]. The system considered for this case study has 10% of WE penetration in a grid of Short Circuit Ratio (SCR) 10. The impact of power grid strength and Phase-Locked Loop (PLL) parameters on

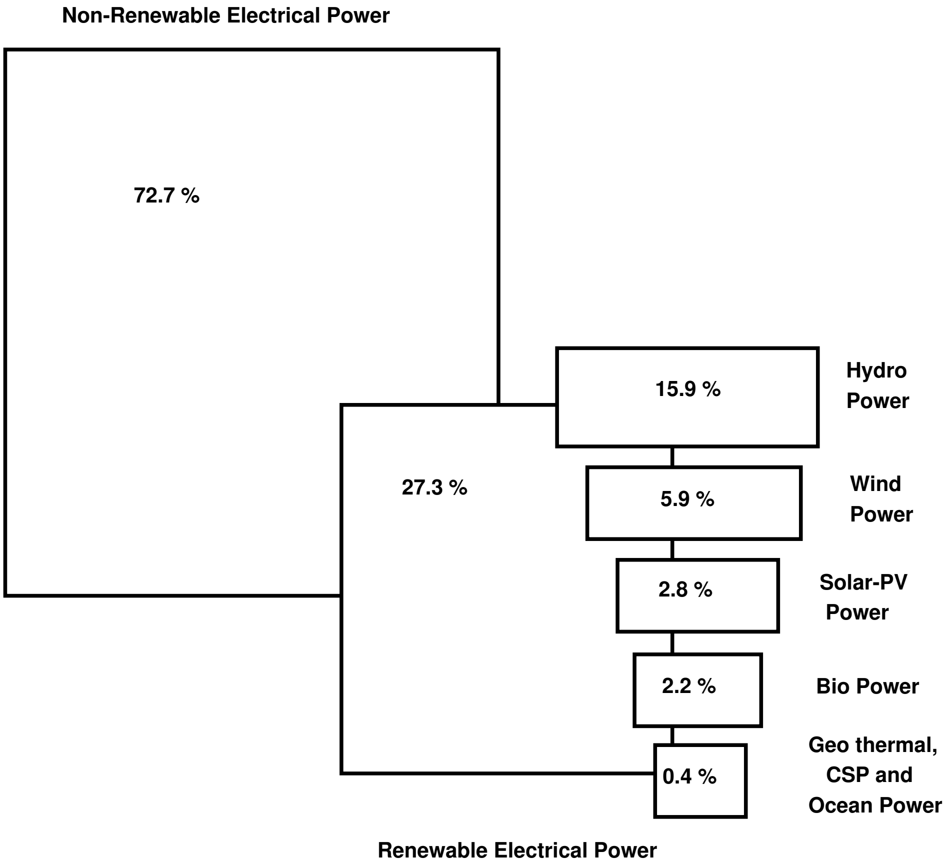

Figure 1.1: Present global scenario of renewable and non-renewable sources.

the stability of the grid-connected to Doubly-Fed Induction Generator (DFIG) has been presented in [Liu *et al.*, 2020a].

In the case of rural grids (weak grids), the reactive power support required is substantially large. Hence the built-in converter of wind energy conversion system may fail to meet the reactive power demand unless it is considered in the design of the converter. Failing to provide the required reactive power supply by built-in converter may lead to voltage instability, and other PQ disturbances [Li *et al.*, 2019b]. This leads to the limited power injection capability of the WE generator. The research studies in [Zhang *et al.*, 2009; Durrant *et al.*, 2003] demonstrate that the power injection capabilities in the weak grid (SCR$\leq$3) and ultra-weak grid (SCR$<$2) are limited due to the power quality issues such as continuous power & voltage variations, flicker, harmonics and reactive power. The research studies at ERCOT test bench proved that the power injection capability is limited to 13% in a grid with SCR of 2 [Huang *et al.*, 2012]. [Zhou *et al.*, 2005] presented various case studies and established that maintaining the voltage stability beyond 20% of WE penetration is a big challenge in the case of a weak grid owing to PQ. Hence, researchers suggested an additional converter with appropriate control technique (at the PCC) to meet the challenges associated with large WE penetration in weak ac grid [Chen *et al.*, 2009]. [Chi *et al.*, 2019], suggested an additional DSTATCOM at PCC to achieve a penetration level of 20 to 30% in the presence of light and induction motor loads at PCC. The performance of additional DSTATCOM is majorly dependent on the control algorithm.

The performance of a PLL based cascaded vector control scheme designed for reactive power management to maintain voltage stability has been presented for a stiff grid in [Muyeen, 2014]. PLL-based current vector control to compensate voltage magnitude and its angle has been implemented while neglecting the DC side voltage dynamics of the converter to maintain the grid's stability with SCRs ranging from 1-10 in the absence of loads at PCC [Givaki *et al.*, 2019]. A dc-link voltage control scheme has been implemented for a DFIG system connected to a grid with SCRs ranging from 1.2 - 4 to improve the stability in [Hu *et al.*, 2015]. However, the performance of this method was found unsatisfactory in the presence of fast transients associated with the system. It can be observed from the literature survey that the performance of conventional control algorithms (in the scenario of the rural grid and the presence of NL loads) is reported to be unsatisfactory. The limitations associated with these control methods include computational complexity, inaccuracy in power tracking and oscillations in DC-link voltage. Modifications /and additions have been suggested in the literature to improve the performance of these algorithms [Hatziargyriou *et al.*, 2020; Chawda *et al.*, 2020]. A hybrid generalized integrator scheme in [Chishti *et al.*, 2020], an intelligent heuristic algorithm in [Zhang *et al.*, 2020], and a coordinated control strategy in [Li *et al.*, 2019a] have been suggested to minimize the inadequacies of PLL controllers in distorted grid conditions without considering the presence of loads at PCC. A wide-band harmonic voltage feed-forward control strategy has been implemented in a grid with an SCR of 2 with considering the resistive loads in [Li *et al.*, 2020a]. A sensor-less virtual flux combined control scheme in [Jabbarnejad *et al.*, 2020] has been implemented for compensating the grid voltage unbalancing and harmonics with considering the load disturbances. But the switching table may create a burden on the computation of reference signals in the presence of NL loads due to requirement of reactive power. However, these algorithms also suffer from the computational burden, fast response, and lack of adaptiveness to change the system. Hence, the researchers have started exploring the capabilities of adaptive algorithms to tackle the challenges in the modern grid. An adaptive non-dominated sorting genetic algorithm in [Chi *et al.*, 2020] and coordinated defensive and restorative control algorithm in [Chi *et al.*, 2019] have been designed for VAR planning to enhance voltage stability in the stiff grid in the presence of 25% induction motor load. The algorithms presented in [Chi *et al.*, 2020] and [Chi *et al.*, 2019] may suffer from a high computation burden under wind power uncertainty. Daniel et al. [Restrepo and Rios, 2019] have developed a model reference adaptive power oscillation damping controller for a stiff grid with 25% WE penetration. [Singh *et al.*, 2007] presented the ADALINE control algorithm for a stiff grid with NL load without wind energy penetration. These adaptive algorithms reported in the literature do not address the combined challenges associated with the weak grid, high level of WE penetration and presence of NL loads. These research studies involving adaptive control algorithms present hope for enhancing WE penetration levels in the scenario of rural grid and proliferation of NL loads by mitigating PQ disturbances effectively. However, there is a need to explore the capabilities of these adaptive control algorithms for various strengths of ac grid under different wind speeds and various percentages of non-linear loads.

1.2 AIM AND RESEARCH OBJECTIVES

A lot of research work has been reported in the literature targeting the enhancement of WE penetration and importance of the power quality issues with the help of different case studies. However, these case studies are found to address the individual challenges associated with low SCR, presence of NL loads, load unbalancing, etc.

The proposed research work is aimed to address the challenges associated with wind energy penetration in weak ac grid in the combined scenarios of variation in wind speed, grid strength and presence of NL loads with the help of an additional DSTATCOM infrastructure controlled by various adaptive algorithms, namely, Adaptive Linear Element-Least Mean Square (ADALINE-LMS) algorithm, Least Mean Fourth Algorithm and Delayed Least Mean Fourth algorithm. The proposed algorithms work on continuously updating the weight component of current and voltage signals based on changes in the system such as grid strength, wind speed, connected loads, and DC-link voltage of DSTATCOM for the estimation of reference gate signals. These algorithms also ensure reliable operation complying with PQ standards due to the attractive features, including simple architecture, simplified calculation, hardware compatibility, PLL-less structure, adaptiveness, minor steady-state error, and power estimation accuracy. The system configuration used for these case studies is a DFIG based wind energy system connected to a weak grid with an additional DSTATCOM in the presence of NL loads at PCC. Hence, the following are the main objectives of the research work presented in this thesis.

- To carry out a state-of-the-art review on the various control algorithms of DSTATCOM for power quality improvement with RE penetration and necessary international PQ standards.
- To carry out a state-of-the-art review on the current global status of WE penetration, challenges and solutions. The additional DSTATCOM infrastructure is a possible solution for enhancing WE penetration levels in the rural grid.
- To carry out design consideration and selection of optimized rating of equipment and components for MATLAB simulation and experimental prototype associated with high WE penetration into the rural grid.
- Design and implementation of methodology based on the additional DSTATCOM infrastructure controlled by adaptive control algorithms. This method injects the required reactive power at the PCC to increase the WE penetration level into the rural grid in the presence of nonlinear loads by mitigating PQ disturbances.
- Design and implementation of adaptive control algorithms in such a way that they consider the changes in wind generation, DC-link voltage and grid voltage for accurate reactive power planning and DSTATCOM size optimization.
- The performance of developed adaptive control algorithms is tested under the combined scenarios of variation in wind speed, grid strength and presence of linear, non-linear loads.

1.3 CONTRIBUTION OF THESIS

The subsections mentioned above have described the importance of mitigating the PQ issues in the rural grid to enhance WE penetration. Therefore, the proposed methods have been tested by simulating unbalance in the system and varying the parameters such as wind speed, SCR, the composition of linear and NL loads under the simulation and experimental environment. The significant contributions of the work presented to enhance WE penetration levels beyond 20% for a rural grid are as follows:

- A comprehensive review of PQ challenges and DFACTS based solutions related to the RE integration into the utility grid are presented. The various conventional and adaptive control algorithms for DFACTS devices are also discussed, along with the design procedure.
- An overview of challenges and solutions associated with the high WE penetration into the rural grid is presented.
- **ADALINE-LMS algorithm:** With this algorithm a WE penetration level of 25% into a rural grid of SCR 2.74 in the presence of 25% NL load has been achieved under a wind speed variation ranging 15 m/s and as low as 7.5 m/s. The accurate signal tracking of this algorithm helps in reducing the size of the DSTATCOM up to 70%.
- **Least Mean Fourth Algorithm:** With this control algorithm a WE penetration level of 25% into a rural grid of SCR 2.74 in the presence of 40% NL load has been achieved under a wind speed variation ranging 15 m/s and as low as 7.5 m/s. The accurate signal tracking of

this algorithm helps in reducing the size of the DSTATCOM up to 80%.

- **Delayed Least Mean Fourth Algorithm:** With this control algorithm a WE penetration level of 30% into a rural grid of SCR 2.74 in the presence of 40% NL load has been achieved under a wind speed variation ranging 15 m/s and as low as 7.5 m/s. The accurate signal tracking of this algorithm helps in reducing the size of the DSTATCOM up to 85%.

- **All the three algorithms** mentioned above now been successful in achieving grid (SCR = 2.74) synchronization of a DFIG within 0.9 seconds in the presence of non-linear loads.

  The simulation and experimental results shows that, the proposed adaptive algorithms have been successful in achieving WE penetration levels as high as 30% into the weak ac grid in the presence of non-linear loads as large as 40% satisfying EN-50160 and IEEE 519-2014 standards.

1.4 LIST OF PUBLICATIONS

International Journal Publications

1. Gajendra Singh Chawda, Abdul Gafoor Shaik, *Enhancement of Wind Energy Penetration Levels in Rural Grid using ADALINE-LMS Controlled Distribution Static Compensator*, in IEEE Transactions on Sustainable Energy, vol. 13, no. 1, pp. 135-145, Jan. 2022, doi: 10.1109/ TSTE.2021.3105423.

2. Gajendra Singh Chawda et al. *Performance Improvement of Weak Grid-connected Wind Energy Using FLSRF Controlled DSTATCOM*, in IEEE Transactions on Industrial Electronics, (Accepted, Manuscript No. 21-TIE-3398.R2).

3. Gajendra Singh Chawda et al. *Comprehensive Review of Distributed FACTS Control Algorithms for Power Quality Enhancement in Utility Grid with Renewable Energy Penetration*, IEEE ACCESS, doi: 10.1109/ACCESS.2020.3000931, vol. 8, pp. 107614-107634, 2020.

4. Gajendra Singh Chawda et al. *Comprehensive Review on Detection and Classification of Power Quality Disturbances in Utility Grid With Renewable Energy Penetration*, IEEE ACCESS, doi: 10.1109/ACCESS.2020.3014732, vol. 8, pp. 146807-146830, 2020.

5. Gajendra Singh Chawda, Abdul Gafoor Shaik, *A Smart Solution for Soft Synchronization of DFIG to Weak Grid with High Wind Energy Penetration*, in IEEE Transactions on Industrial Informatics, Under Review.

6. Gajendra Singh Chawda, Abdul Gafoor Shaik, *Power Quality Mitigation in Rural Grid using Adaptive Control Algorithm for Enhancing Wind Energy Penetration*, in IEEE Transactions on Smart Grid, Under review.

7. Gajendra Singh Chawda, Abdul Gafoor Shaik, *Power Quality Enhancement in Weak Grid using Adaptive Algorithm with High Wind Energy Penetration Level*, Manuscript ready - to be communicated in IEEE Transactions on Power System.

International Conference Proceedings

1. Gajendra Singh Chawda, Abdul Gafoor Shaik, *Power Quality Mitigation in Weak AC Grid with Low X/R Ratios using Distribution Static Compensator Controlled by LMF Algorithm.* In 2020 IEEE Region 10 Symposium (TENSYMP), pp. 44-47. IEEE, 2020.

2. Gajendra Singh Chawda, Abdul Gafoor Shaik, *Performance evaluation of adaline controlled dstatcom for multifarious load in weak ac grid* In 2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia), pp. 356-361. IEEE, 2019.

3. Gajendra Singh Chawda, Abdul Gafoor Shaik, *Smooth grid synchronization in weak ac grid with high wind energy penetration using distribution static compensator* In 2019 2nd International Conference on Smart Grid and Renewable Energy (SGRE), pp. 1-6. IEEE, 2019.

4. Gajendra Singh Chawda, Abdul Gafoor Shaik, *Adaptive reactive power control of dstatcom in weak ac grid with high wind energy penetration* In 2019 IEEE 16th India Council International Conference (INDICON), pp. 1-4. IEEE, 2019.

5. Gajendra Singh Chawda, Abdul Gafoor Shaik, *Fuzzy logic-based control algorithm for dstatcom connected to weak ac grid* In 2018 2nd International Conference on Power, Energy and Environment: Towards Smart Technology (ICEPE), pp. 1-6. IEEE, 2018.

Book Chapter

1. Gajendra Singh Chawda, Abdul Gafoor Shaik, Om Prakash Mahela, *Higher Levels of Wind Energy Penetration into the Remote Grid*, Active Electrical Distribution Network: A Smart Approach, John Wiley & Sons ISBN:9781119599517, 2021.

1.5 STRUCTURE OF THE THESIS

This thesis is organized into six chapters as follows.

Chapter-1 This chapter provides a detailed problem statement, aim, research objectives and significant contribution of thesis work. The organization of thesis chapters includes the system configuration, design of adaptive algorithms, extensive simulation studies, hardware studies are presented to validate the findings of simulation studies, the comparative analysis of the proposed adaptive algorithm with other algorithms, and the research work's conclusions.

Chapter-2 This chapter presents a review of research work reported in the literature including power quality associated with renewable energy, challenges and international standards, especially wind energy sources. Distributed-FACTS devices and the role of conventional and adaptive control algorithms for PQ improvement and the optimal switching of DSTATCOM are discussed in detail. The identified research gaps are also presented at the end of the chapter.

Chapter-3 This chapter presents detailed case studies for establishing the ADALINE-LMS-based adaptive control algorithm's performance to enhance WE penetration level in the rural grid by mitigating various power quality disturbances under the MATLAB and experimental environment. Finally, the effectiveness of the proposed algorithm has been compared using algorithms published in the literature.

Chapter-4 This chapter presents detailed case studies for establishing the adaptive Least Mean Fourth control algorithm's performance to enhance WE penetration level in the rural grid by mitigating various power quality disturbances under the MATLAB and experimental environment. Finally, the effectiveness of the proposed algorithm has been compared using algorithms published in the literature.

Chapter-5 This chapter presents detailed case studies for establishing the Delayed Least Mean Fourth based adaptive control algorithm's performance to enhance WE penetration level in the rural grid by mitigating various power quality disturbances under the MATLAB and experimental environment. Finally, the effectiveness of the proposed algorithm has been compared using algorithms published in the literature.

Chapter-6 This chapter summarises the proposed research work findings, and scope for future work.