Enhancement of Transmission Systems Operational Condition in a Large Scale Wind Integrated Power Systems Against Extreme Weather Events

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Abstract— **Increasing extreme weather events, partly driven by climatic issues/global warming, motivated relevant studies and planning for strengthening power system resiliency. Due to such highly impactful weather events, power systems infrastructure and operation are significantly affected. Therefore, to minimize the impact and the extent of the event-driven damage to the grid, there is a pressing need for adequate preventive and resiliency planning. This paper presents an approach to improve the voltage and the line loading profiles of large-scale wind integrated power systems during such disruptive events to maintain the reliability of the healthy part of the transmission systems during/after the event. This study considers outages of multiple buses, transmission lines, loads, and generators. By exercising the volt-var control at wind farm buses during these contingencies (failure of different buses, loads, and generators), the operational profile of the healthy part of the systems has been improved. The developed strategy has been tested on the IEEE-39 bus system designed in DIgSILENT Power Factory. The work outcomes show that volt-var control significantly improves the operational profile of the healthy part of the system with an increasing penetration level of wind generation during and post extreme events.**

Keywords—resiliency, transmission systems, volt-var control, wind power generation

I. Introduction

The modern electrical infrastructure transmits the bulk of electricity from power plants to remote demand locations. The high-voltage transmission networks that act as a backbone to these systems play a critical role in the bulk transmission of power. As transmission networks are exposed to extreme situations that potentially lead to physical damage to overhead transmission lines and towers, their ability to transmit reliable power is impaired. The extreme events may include ice storms, hurricanes, cyclones, and thunderstorms. This occurrence of such detrimental wind events causes damage to the power system and loss of reliability. So, planning is essential while studying such events and maintaining the system's line loading and voltage profiles. The control strategy must keep these profiles during such extreme weather [1] events. The goal of the healthy power system is to be resilient and reliable even in the context of such extreme weather events.

A. *Literature Review*

Resilience is essential in critical infrastructure systems like electric power grids since it relates to a system's ability to absorb and adapt to [2] extreme occurrences. External shocks to the electricity infrastructure can take many different forms; the most well-known are catastrophic events like severe weather and natural catastrophes [3]. Both have been found to have serious adverse effects on the grid and society. [4] In the discipline of ecology, Holling was the first to develop the theory of resilience for complex systems [5]. After an unusual event, Holling identifies the frequency and speed with which a system returns to normal conditions. [6]. Resilience research aims to predict unanticipated changes resulting from loss and failure while considering that networks have constraints. The environment has an ongoing impact on structure and external disruptions [7]. In the post-disaster period, a restoration model based on power flow limits is proposed to reduce the economic loss due to load disturbances, and it produces an ideal [8] strategy utilizing the macroeconomic definition of the value of lost load (VOLL) [9]. Electric companies in the United States invest a lot of money in dynamic and preventive operations like grid hardening [10].

Companies, governments, and investors have learned from these outages that faults can expand across regional and global power systems, changing a local occurrence into a socioeconomic disaster [11]. Traditional power systems are subject to long-term power outages that are difficult and time-consuming to recover from, making them insecure and vulnerable [7]. Maintaining the electric energy system's critical infrastructure in its current state is a well-known security and resiliency concern [2] and the foremost hurdle to developing intelligent transport systems and renewable grid integration [12]. Fig. 1 gives us insights into renewable connected transmission networks and the effect on the system (outages taken) due to wind events like cyclones or hurricanes. When such a wind event happens, the power system would have numerous obstacles sustaining system voltage and line loading profiles. Network infrastructure refers to a network that is resilient in all aspects. The total picture of renewable integrated grid resiliency in extreme wind events is depicted in Fig. 1.

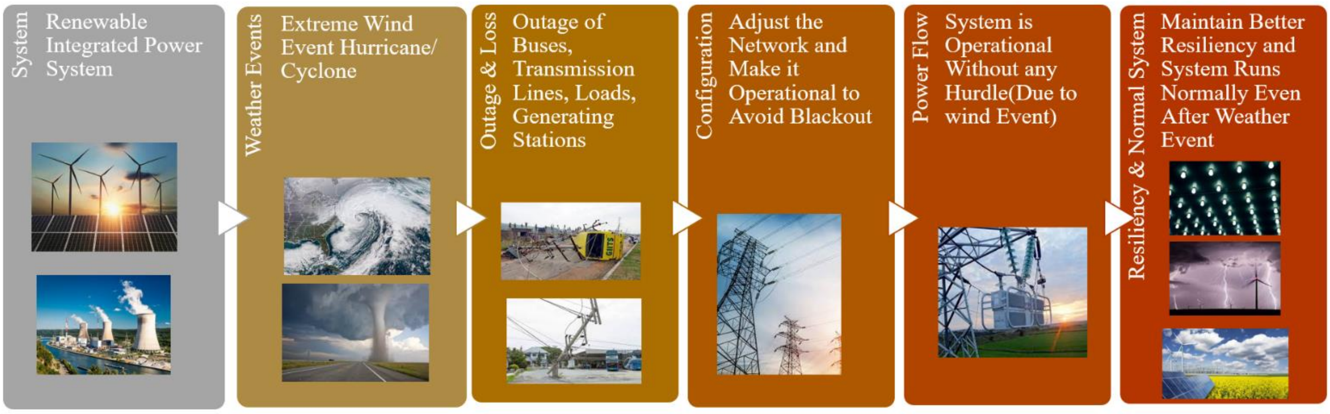

Fig.1. Renewable Integrated Grid Resiliency in Extreme Wind Events

B. Contribution Of This Study

The above literature survey shows that the transmission line resiliency analysis is the need of the hour. With the increase in renewable penetration, the operation of power systems during and after an extreme weather event becomes more critical. Depending on the magnitude of the weather events, the function of the healthy part of the system may be impacted during and post extreme weather conditions. Many works of literature have addressed the planning aspects to enhance the transmission systems resiliency but rarely discussed the strategy to improve the operational profile (voltage and line loading, etc.) of the healthy part of the transmission network during and after a destructive weather event on a large scale renewable penetrated power systems. Against this backdrop, this work presents a control strategy that incorporates Volt-Var control from wind power plants during and after extreme weather events to improve the transmission network's voltage and line loading profiles.

II. Power System Transmission resiliency

The majority of power outages occur regularly around the world [13]. Even the United States, one of the most advanced transmission grid networks, has witnessed an almost 265 percent increase since 1984. When three of India's linked grids collapsed, the country experienced its largest blackout. This disaster has crippled subways, clogged traffic, and trapped miners have touched over 670 million people [10]. As a result, one of the significant challenges and new research for the power business is maintaining adequate power system transmission resiliency [7]. One of the questions might be there at what instances resiliency is required? Or at what events resiliency of transmission line needs to be pointed out. So, extreme wind events or natural calamities, increased abrupt loads, high renewable energy (RE) penetration, aging infrastructure, a deficit in sources of supply, cyber-attacks, and the most dangerous is extreme wind occurrences. It is challenging [19] to maintain resiliency in such events. Resiliency is nothing but the rapid system recovery (physically as well as electrically) after the events [18], as such events described above. This paper mainly focused on extreme weather events like wind events. Due to such extreme wind events, system disturbance is followed by improving the line loading profile and voltage profile [14][15] of a system which means system health is explained in this paper. Further, to improve transmission resiliency, planning and study are required. After such weather events in the future, our transmission system must be [16] able to withstand and operate reliably [17]. This paper contributes toward renewable integrated transmission resiliency. As renewables are in high demand, it means continuously increasing with higher penetration into the grid; hence it is necessary to work on resiliency.

III. Methodology

Extreme weather events, such as cyclones, hurricanes, etc., severely affect renewably integrated power systems. Due to these extreme weather events, some parts of a power systems get disconnected, and some remain connected. During these events, the power systems healthy part should not affect. This paper is about maintaining the operational reliability of power systems during such extreme weather events. Impacted buses, transmission lines, loads, and generating stations are out due to extreme weather events shown inside the red box area in fig. 2. This methodology aims to maintain the operational reliability of healthy parts during and post extreme weather events using a volt-var control strategy from wind farm buses.

The outline of the methodology has been described in the flow chart in fig. 3. Time series wind profile data and load data have been used for the study. The time used for the simulation is 3 hours. The study has been carried out with variable penetration in power systems and validated with real-time series wind and load profiles. The sequence of the event has explicitly given in the flowchart in fig. 3. The flowchart provides an overview of using the volt-var control strategy by the wind farm buses to maintain operational reliability, which means the power systems voltage and line loading profile.

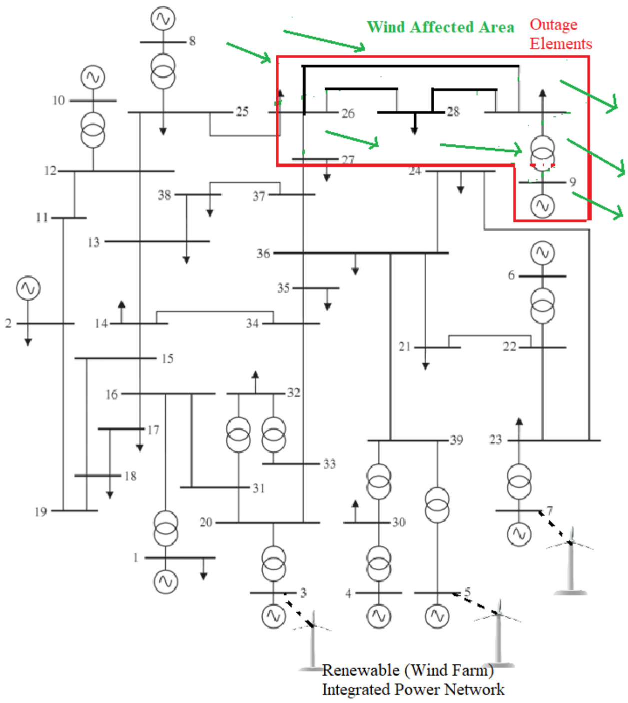

Fig. 2. IEEE 39 Bus System with Renewable Integrated (different penetration) Grid in Extreme Wind Events

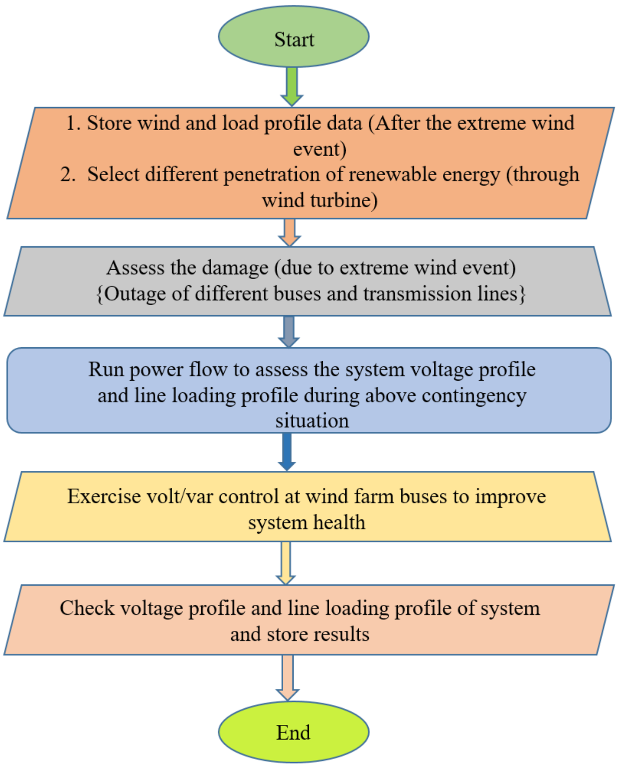

Fig. 3. Flow Chart for Renewable Integrated Grid Volt-Var Control

A. *Mathematical Formulation*

Whenever extreme wind events occur, some of the lines may get out, which causes overloading of lines, and the voltage of adjacent buses may be reduced. To improve the voltage profile, additional control action is required. The volt-var control could be one of the control actions from wind farm buses to improve power systems operational profiles. In this methodology, a volt-var control has been implemented to maintain the health of power systems during extreme weather events by wind farm buses.

In the voltage-dependent reactive power mode of control shown in fig. 4, the DER must regulate its reactive power output as a function of voltage simply at point-of-connection, following a specified piecewise linear characteristic.

In this case of work, voltage-reactive power relation assists in mitigating unacceptable voltage situations created by the voltage conditions during extreme weather events.

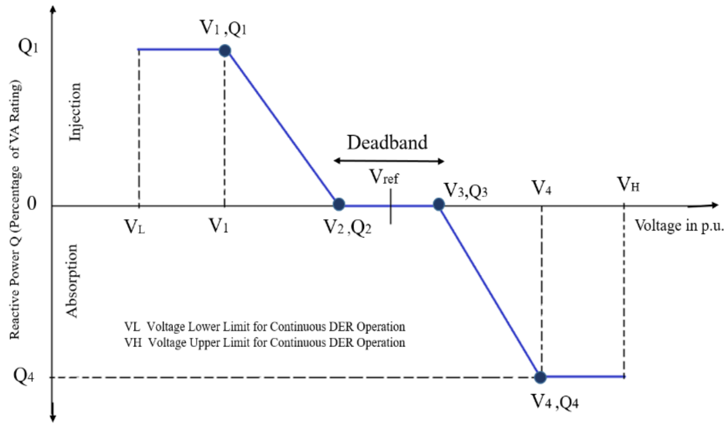

Fig. 4. Standard Voltage Reactive Power Characteristics [15]

This volt-var control aims to maintain the voltage profile and transmission line capability within the limit of the healthy system during and post extreme weather events. So , apart from power flow equations, the constraints involved are given by (1) and (2).

As voltage should lie in the range is shown in (1)

$$V_{ibusmin} \leq V \leq V_{ibusmax} \qquad \text{Where, } i = 1,2,3,\ldots n \qquad (1)$$

Here voltage limits are standard as per the CEA regulations.

For line loading conditions,

$$S \leq S_{imaxloading} \qquad \text{Where, } i=1,2,3,\ldots n \qquad (2)$$

Reactive power injection and absorption take place to improve power systems' health in terms of voltages at the nodes and line loading profiles. Reactive power injection from wind farm bus could be positive or negative depending upon the system requirement.

Whenever the bus voltage violates limits accordingly capability of wind farm bus supply var by volt-var control when buses and lines (power system components) are out, the system becomes not operationally reliable, and power systems operational profiles are not within the permissible limits. Some lines become overloaded, and some are underloaded. To make the system into normal operating conditions, reactive power, i.e. volt-var, improves system conditions, as discussed in this paper.

IV. Results and Discussion

The healthy operational part of the system is severely impacted due to extreme weather events like hurricanes, cyclones, etc. which results in some parts of power systems getting disconnected. So, there is a need to take care of the operational reliability of the healthy part of the power transmission systems. This study intended to simulate the impact of extreme weather events on the operational reliability of the healthy portion of the power transmission network during and post extreme weather events. In this context, this study has been carried out on IEEE 39 bus system on DIgSILENT power factory simulation platform. Fig. 2 shows a hurricane of magnitude class 5 passing over an area, which has been marked in the red box in the figure. It is considered that the buses and transmission lines of the highlighted area (in the red box) get disconnected during the event. As the system has sufficient wind power penetration, so it could assist in the improvement of the operational profile of the healthy part of the systems by appropriate control measures. In this study, volt-var control strategy from wind farm buses has been exercised to improve the system operational profile. Further, this study has observed operational parameters like voltage and line loading profile of the healthy part of the system with different wind power penetration levels.

The following cases have been studied in this paper.

Case I – 15 % wind penetration
Case II- 30% wind penetration
Case III- 45% wind penetration

A. Case I – 15 % Wind Penetration

In this case, 15 % wind penetration has been considered. Fig. 5 and Fig. 6 represent the voltage profile and line loading profile respectively. Due to the space constrained only the voltage profile of bus six has been shown in Fig. 5. The two cases have been studied, i.e. without volt-var control and with a volt-var control strategy. The outage segment of the transmission systems has been shown in Fig. 2. Blue and orange curves represent without and with volt-var control respectively.

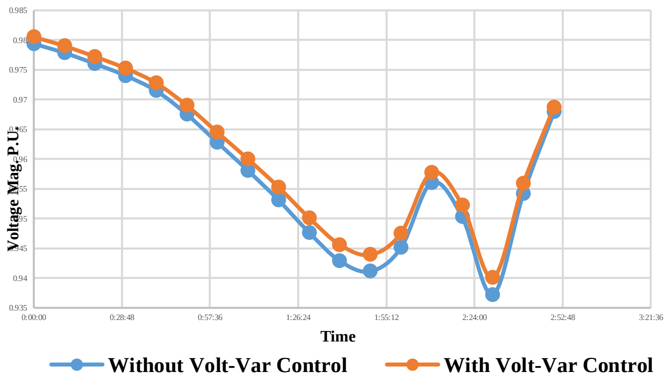

Fig. 5. Voltage Profile of healthy part for 15 % Wind Penetration (Bus 6)

Fig. 6 shows the line loading profile for a line joining buses 23 and 24 only due to space constraints.

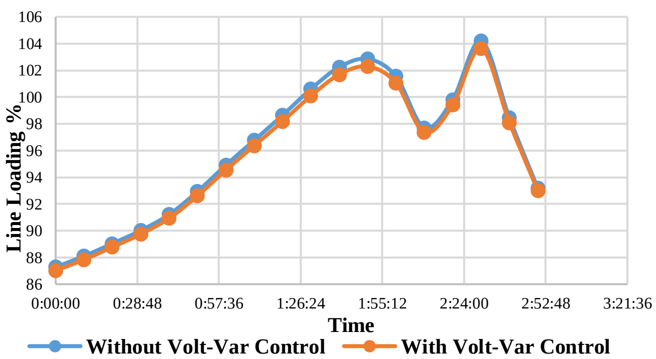

Fig. 6. Line Loading Profile of healthy part for 15 % Wind Penetration (Line 23-24)

B. Case II – 30 % Wind Penetration

In case II wind penetration of 30% has been considered. Fig. 7 and Fig. 8 represent the voltage profile and line loading profiles at all 39 buses with Volt-var control and without Volt-var control mode, respectively. The zero voltage shown in the following figures represents that the buses are outaged due to the hurricane. The line loading profile at all buses for this case is shown in Fig. 8.

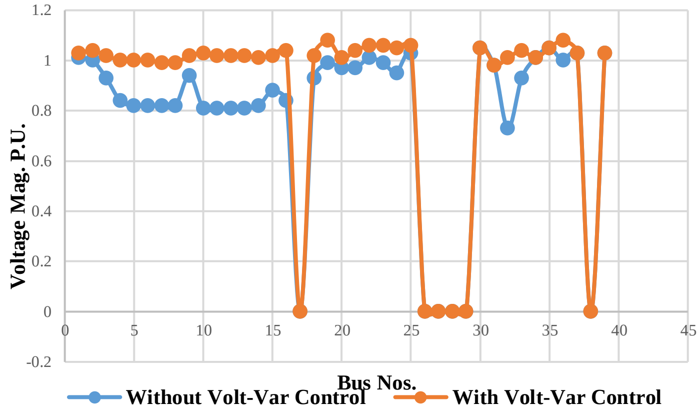

Fig. 7. Voltage Profile of healthy part for 30 % Wind Penetration

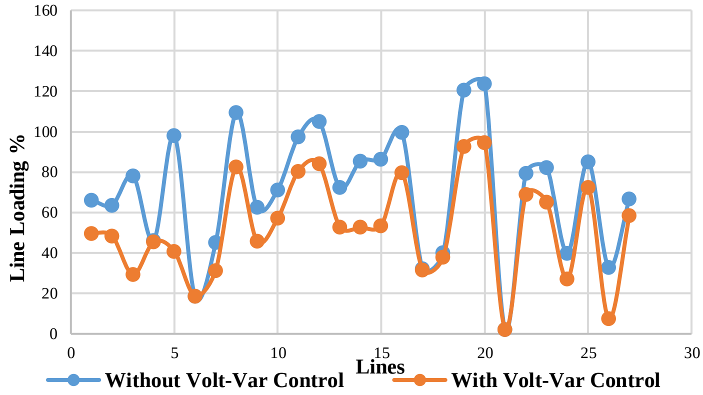

Fig. 8. Line Loading Profile of healthy part for 30 % wind Penetration

C. Case III – 45 % Wind Penetration

In this case, wind penetration of 45 % has been considered. Fig. 9 and Fig. 10 represent the voltage profile and line loading profile of all the 39 buses. The blue and orange curves show the control strategy without and with Volt-var control respectively.

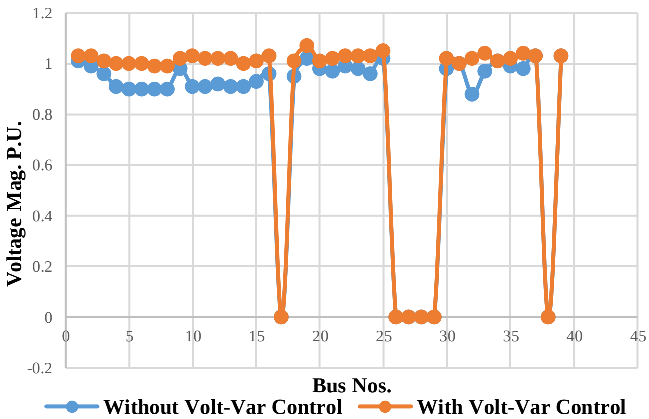

Fig. 9. Voltage Profile of healthy part for 45 % wind Penetration

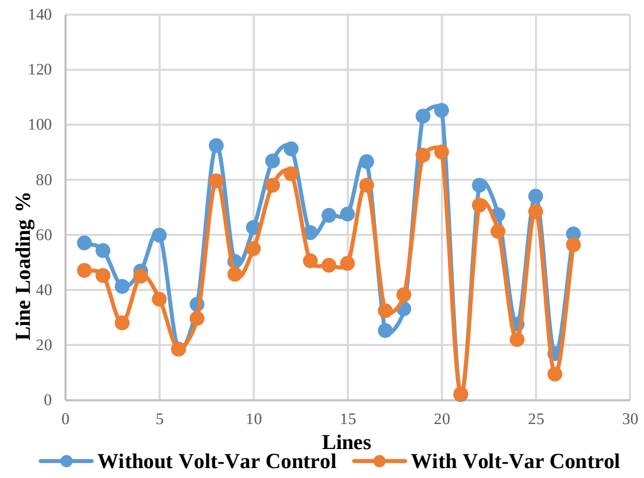

Fig. 10. Line Loading Profile of healthy part for 45 % wind Penetration

D. Observation and Discussion

From the above cases, it is clearly evident that in case I, i.e., when 15 % wind penetration is there, an improvement in system profile (i.e. voltage profile and line loading profile) is marginal, it can be seen in Fig. 5 and Fig. 6. When penetration level increases, as discussed in case II and case III, which has 30% and 45% penetration respectively, improvement in the voltage and line loading profile is much more evident (from Fig. 7 to Fig. 10). There is a significant improvement in voltage profiles and line loading profiles when compared without and with the Volt-var control strategy in all the three cases. Further, in cases II and III, where the reactive power availability in the system is higher, the voltage improves significantly and goes towards overvoltage region in some buses as shown in Fig. 7 and Fig. 9. The line loading profile improves to a great extent as the penetration level increases as shown in Fig. 8 and Fig. 10, when Volt-var control is used better improvement in line loading profile is evident. Overloading till 120% in case II and 105% in case III were observed on several lines before applying the Volt-var control strategy, the application of Volt-var control completely remove the overloading condition of the lines and improve the ATC (Available Transmission Capability) margin.

For all three cases voltage profiles at bus 6, have been observed in Fig. 11 (due to space restriction voltage profiles of other buses could not be shown). As wind penetration increases, the voltage profile has significantly increased for a certain extent, after that voltage profile of some buses breaches the over-voltage limit. Fig. 11 shows the bus voltage profile for bus number 6 for four hours duration while applying Volt-var control for all cases.

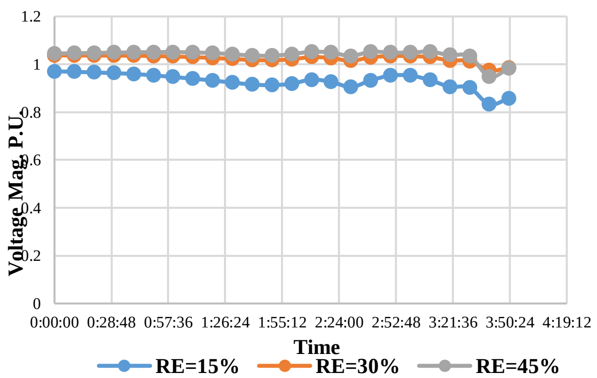

Fig. 11. Voltage Profile of healthy part for different % wind Penetration

Similarly, increased wind penetration level improves line loading profile, which is clearly shown in Fig. 12 (line loading profile of line connected between bus 23 and 24 is shown in Fig. 12). Further, it has been observed that if wind penetration increases beyond 45 %, the excessive reactive power available in the system may lead to overvoltage in some of the buses, while considerably improving the line loading profile.

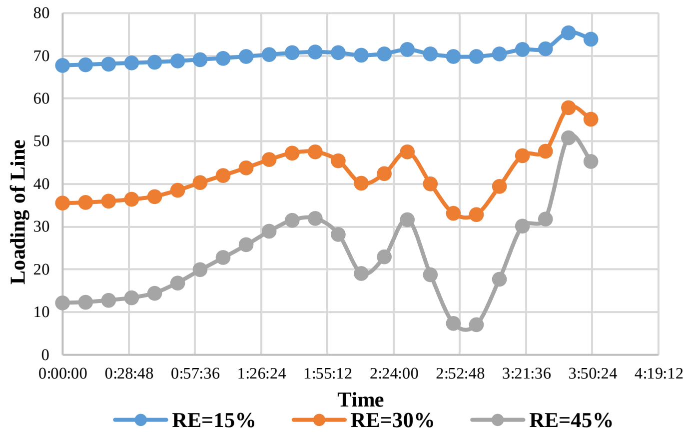

Fig. 12. Line Loading Profile of healthy part for different % wind Penetration

V. CONCLUSION

Extreme weather events like hurricanes, cyclones, etc., significantly impact the power system's operation. This natural phenomenon gives severe contingency issues in the system's operation. The reliable Operation of the healthy part of the system during and post events is of significant concern. This paper implements a control strategy to improve the system operational profile in a power system with a high wind power share. In this context, the volt-var control strategy from wind farm buses has been exercised. The key findings of this study are summarized below,

- A healthy operational part of the system has significantly been impacted during and after extreme wind events. So, preventive control action is required to enhance the operational reliability of a healthy part of the power systems.
- Volt-var control from wind farm buses is an effective control strategy to improve system voltage and line loading profile.
- As wind penetration increases, volt-var control effectively improves system health in line loading and voltage profile. But, with excessive wind penetration, system voltage may lead to an overvoltage condition in the systems. Table 1 shows the system profile level of improvement for different wind power penetration considered in this study.

TABLE 1: Analysis of Operational Profiles for Different Penetration Levels

Wind Penetration	Voltage Profile Improvement	Line Loading Profile Improvement
15%	Not Significant	Not Significant
30%	More Significant	More Significant
45%	Significant but towards overvoltage	More Significant

In the future, this study can further be extended to improve the resiliency of entire power systems using an optimal restoration approach.

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