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Impact of COVID'19 Pandemic on Indian Electrical Distribution System

V. V. S. N. Murty Vallem[1] **and Ashwani Kumar Sharma**[1]

[1] *Electrical Department, NIT Kurukshetra, Haryana, India*

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Abstract: Many countries have imposed nationwide lockdown as a preventive measure against spread of COVID-19 pandemic. In this situation, industrial and commercial loads have been shut down. Consequently, the grid is experiencing sudden decrease in electricity demand. This sudden fall in load demand has a huge impact on power system operation in terms of energy dispatch, reactive power management, voltage security and voltage stability. This paper presents operation of Indian power distribution system, during unexpected COVID-19 and lockdown measures. Electricity demand on Indian power sector has dropped quickly with confinement measures. Rise in electricity demand observed, as unlock measures were gradually implemented. Power demand in India declined by 21.3% on 25th March 2020 & 30.8% on 27th March 2020 when lockdown measures implemented. Peak power consumption had declined by 20.3% in April, 16.3% in May and 5.3% in June compared to the same months last year. Consequently, gap between thermal and renewable power generation decreased to match power balance. It is noted that market clearing price declined by 21% during lockdown period and the lowest MCP recorded is 1.952 Rs./KWhr on 25th March 2020. The main objective of the network operator is to ensure 24x7 uninterrupted and quality power supply to all consumers. Voltage and frequency profile shall be maintained within Indian Electricity Grid Code band. In order to prevent the blackouts, network operator has to analyze the power system in advance in the aspect of voltage security for a wide range of uncertainties to evaluate potential risks to the system. Indian power system management is reported in this paper during COVID-19 and it's impact on voltage profile, reactive power management and market clearing price. In this paper, looking into adverse effect of declined load demand, an analysis has been carried out on Indian electrical distribution system for such events in future. A detailed voltage stability analysis is also carried out and cause for voltage instability is identified. Modal analysis is also performed to identify weak nodes and lines using participation factors. Accordingly, corrective action is taken to improve voltage stability margin. Further, PV and QV curves are obtained at each node using continuation power flow to demonstrate loadability limits. Nodes with least stability margin are critical. The analysis has been carried out on practically existing part of Indian Distribution System with realistic load profile.

Keywords: Load Demand, Voltage Management, Voltage Stability, Reactive Power Management, PV Curve, QV Curve, Distribution System

1. INTRODUCTION

The present power system is operating in highly load stress conditions and is vulnerable to face numerous challenges in terms of voltage, transfer capability, stability, and security. The power system operating point should be stable and secure, subject to various operational constraints under normal and contingency scenarios. The network operator need to initiate appropriate measures timely to improve voltage regulation, system stability and security and minimize energy losses. The distribution networks are operating at verge of voltage stability limits due to economic and environment constraints. Voltage stability problem is significant since it affects the power system security and reliability. Voltage stability is the "ability of a power system to maintain steady acceptable voltages at all buses under normal conditions and after being subjected to a disturbance" [1]. Therefore, maintaining voltage stability in the present power systems is a challenging task for the system operator which is essential for power system planning and operation. Voltage stability margin is the difference between operating point to voltage collapse

E-mail: murty209@gmail.com, ashwani.k.sharma@nitkkr.ac.in

point. Security of distribution system in the aspect of voltage stability is, to determine the most critical voltage point. The key driving factors for voltage instability are inadequate reactive power support, outage of lines, generators and transformers. Sudden disturbances of reactive power may push the system to the verge of voltage instability region [2]. In addition to this, unexpected global pandemics like COVID-19 has a huge impact of voltage stability of the system due to sudden change in electricity demand due to confinement measures taken to prevent COVID-19 spread.

Various conventional approaches such as PV and QV curve, continuous power flow [3, 4] and singularity of Jacobian matrix [5, 6, 7, 8, 13] exist to analyze voltage stability phenomenon. In [9, 10, 11], network was reduced using branch equivalent based approaches. Maximum allowable loading values were determined in radial distribution system subject to voltage stability [12]. A new voltage stability index was formulated for radial distribution systems based on network load admittance ratio [14]. Dynamic voltage stability margin estimated using machine learning based program [15]. Static voltage stability margin calculated for a power system with high wind-power penetration using interval optimization theory [16]. Critical developed voltage and reactive power sensitivity Indices were in [17] to identify voltage instability of power system. A novel voltage stability assessment algorithm proposed in [18] to determine voltage stability of electrical distribution system and loadability limit estimated using PV curves. Voltage stability enhancement was reported in [19] using UPQC. In [20], multi-objectives of minimization of operation cost, emission indices and maximization of customer satisfaction considered in hybrid energy system model and solved using Shuffled frog leaping algorithm. Economic, environmental and reliability indices were included in energy scheduling problem and solved using decision making approach [21]. Energy scheduling problem was addressed using augmented ε-constraint method for multi-objectives of economic, environmental indices and load shifting [22]. Day-ahead scheduling problem of microgrid was modeled as a multi-objective function consisting of: minimizing the operation cost, load curtailment cost and emissions. The optimization problem was solved using ε-constraint approach in GAMS [23].

Due to the lockdown in the wake of COVID-19, industrial and commercial activities have been shuttered. In such a troubling situation with the need of ‘social distancing’ to prevent spread of COVID-19, employees are working from home. Significant increase in residential load demand is observed as the employees are working from home during the lockdown period. Moreover, hospital load is also increased to provide essential services. This leads to unexpected steep fall in load demand on the grid, which leads to voltage rise beyond permissible limits and voltage instability issues. The steep fall in energy consumption will have impacts of energy management, voltage rise and voltage instability issues which is a challenging task for grid operators during this critical situations. It requires, actions of scale down the generation to maintain supply-demand balance, and Volt-VAR control actions to regulate voltage profile. Further, under light load conditions, capacitor banks shall be switched off and OLTC to be set at nominal position to maintain nominal voltage. Also, shunt reactors and D-STATCOM (voltage control mode) shall be suitably deployed at appropriate locations to control over voltages. Distribution network operator at control center need to monitor change in load demand, bus voltage and reactive power reserve closely. Moreover, PV power generation is increasing during the summer period which requires an effective co-ordination and energy management with other generation systems for grid balancing and economic operation. Flexible generation sources are essential to fill the peak and valley gaps in the load curve. Therefore, further analysis is required to evaluate the impact of unexpected global pandemics on power system operation and planning aspects to estimate potential risk to the network. The main contributions of the paper are:

(i) Voltage management and voltage stability issues are discussed considering sudden fall in load demand.

(ii) Indian power system management is reported during lock down period of COVID-19.

(iii) Further, modal analysis is also performed to identify weak buses and branches.

(iv) Moreover, PV and QV curves are determined using continuous power flow approach to estimate maximum loadability limits.

(v) Voltage profile is maintained within acceptable range by installing D-STATCOM.

(vi) Even after unlock period, rise in the electricity consumption from various industries will depend on supply-demand chain and is hard to predict, vary from one sector to another sector. The system operator has to collect and analyze the load demand pattern during this scenario and need to prepare monthly-ahead scheduling as well as any unforeseen incidents.

The paper is organized as follows: Indian power system operation is explained in Section 2. Section 3 deals with modal analysis. Numerical results are discussed in Section 4. Finally, the conclusions are reported in Section 5.

2. IMPACT OF COVID-19 LOCKDOWN ON INDIAN POWER SYSTEM

World Health Organization (WHO) has declared on 11th March 2020 that COVID-19 is a pandemic. On 25th March 2020, Indian government has announced an unprecedented 21-day lockdown to prevent spread of COVID-19 pandemic. Subsequent lockdown and unlock phases are given below:

Lockdown:

- Phase 1: 25th March 2020 – 14th April 2020
- Phase 2: 15th April 2020 – 3rd May 2020
- Phase 3: 4th May 2020 – 17th May 2020
- Phase 4: 18th May 2020 – 31st May 2020

Unlock:

- Unlock 1.0: 1st June 2020 – 30th June 2020
- Unlock 2.0: 1st July 2020 – 31st July 2020
- Unlock 3.0: 1st August 2020 – 31st August 2020
- Unlock 4.0: 1st Sept 2020 – 30th Sept 2020

During the lockdown period, industrial and commercial activities are shutdown. Reduction of commercial and industrial load demand will likely cause a natural increase in residential load as employees are working from home and people are restricted to stay at home. Majority of residential loads are lighting, laptops, heating/AC, dishwashers etc. Under such situation of drastic decrease in the load demand, the system voltage will rise and the electrical equipment will be stressed due to considerable rise in the voltage. This may lead to failure of the electrical equipment and system voltage stability may jeopardize.

When unlock measures implemented in June 2020, the power demand increased gradually. With resumption of economic activities, power consumption as well as demand would start recording yearly growth from September. Power consumption rose 0.9% on 1st September 2020, indicating spurt in commercial and industrial demand for electricity.

In this situation, home energy management and demand response participation could have significant impact on energy efficiency operation of the system. Network operators has to encourage residential consumers to participate in demand response program and use their electrical appliances during off-peak period at extent possible. In this context, on 22nd March 2020: Janta Curfew was imposed, from 25th March – 14th April 2020: All-India containment measures, 5th April 2020: Lighting switch off event was implemented at 21:00 hrs for 9 minutes, from 14th April – 16th May 2020: Extension of all-India containment measures have been enforced.

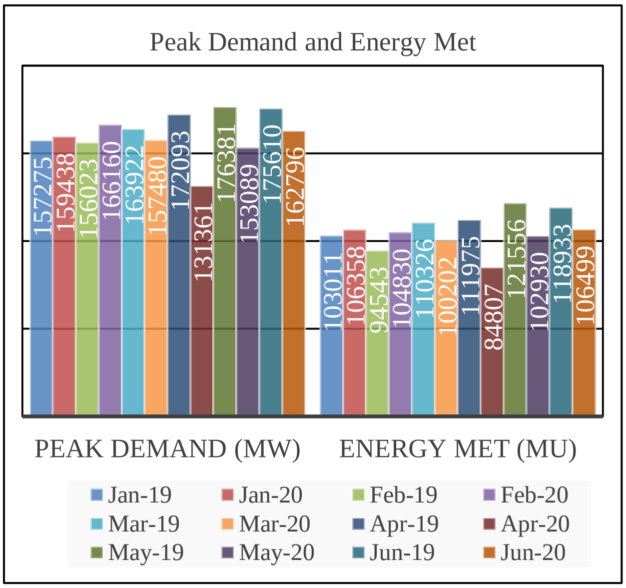

Figure 1. All India peak demand and energy met during management of COVID-19 in comparison to 2019 [24]

The impact of load demand variation on Indian electricity sector is more evident than ever before. However, the power system is not immune to the adverse effects of the pandemic that has arisen in the past few months. The long-term impact of the current situation would only become apparent as the time lapses. Some early impacts of COVID-19 on Indian power system is already becoming an evident as reported by Power System Operation and Corporation (POSOCO) [24]. POSOCO through its five Regional Load Dispatch Centres (RLDCs) and the National Load Dispatch Centre (NLDC) has taken preventive steps to ensure reliability of Indian electricity grid during COVID-19 pandemic outbreak. Energy met during lockdown period in comparison to 2019 is depicted in Fig. 1. All India maximum demand during the management of COVID-19 in comparison to 2019 is shown in the Figs. 1-2. During the lockdown period, peak power consumption is reduced around 15% - 26% [24]. Country's overall energy consumption is dropped from 3,586 GWh on 18th March to 2,652 GWh on 26th March. It is observed that in the month of March’20, the demand has drastically reduced compared to the year 2019. The energy reduction during the April month is quite visible as compared to the energy met in the year 2019 [24].

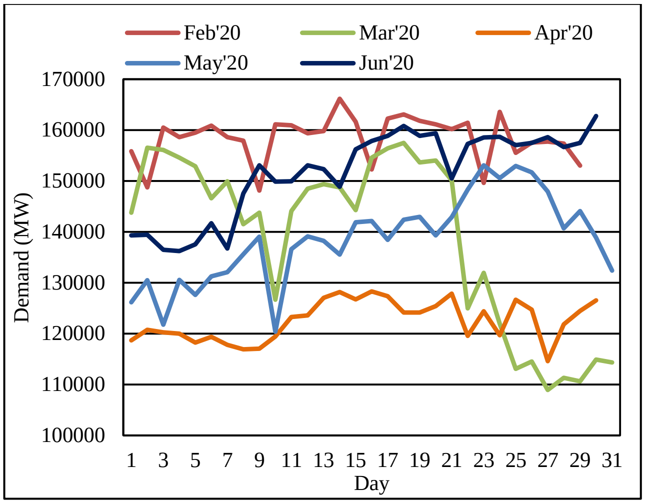

Figure 2. All India daily peak demand during management of COVID-19 [24]

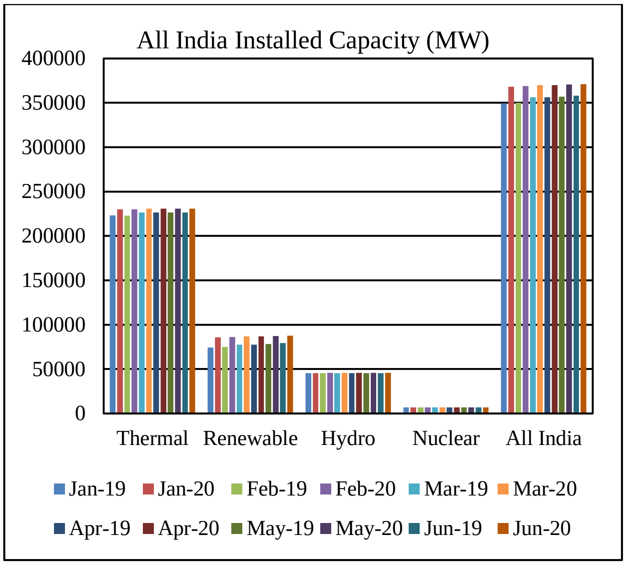

Figure 3. All India installed capacity during management of COVID-19 in comparison to 2019 [26]

All India installed power capacity is increased to 370048 MW from 356100 MW as shown in Fig. 3. 13948 MW capacity is added during financial year 2020 in comparison to 2019. In FY20 4531 MW of thermal capacity was added representing 2% increase; 9117 MW of renewable capacity was added representing 12% increase and only 1% increase was recorded in hydro with the installed capacity addition of 300 MW while the nuclear capacity remains the same during the fiscal year at 6780 MW. All India peak demand in FY20 increased by 6782 MW representing 4% from 177022 MW to 183804 MW over FY19. All India energy met increased by 16,164 MU representing increase of 1% from 1267526 MU in FY19 to 1283690 MU in FY20.

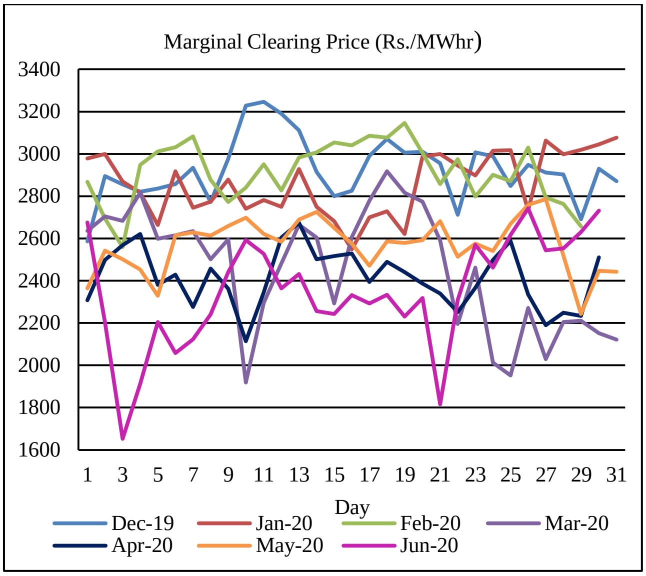

Figure 4. Clearing price during management of COVID-19 in comparison to 2019 [25]

Following four markets segments are available in Indian electricity market [25]: Day-Ahead Market (DAM), Term-Ahead Market (TAM), Renewable Energy Certificates (REC), and Energy-saving certificates. Recently, real-time electricity market (RTM) was implemented in India and RTM came into operation at Indian Energy Exchange (IEX) and Power Exchange India Limited (PXIL) from 3rd June 2020 [25, 26]. The RTM mechanism enable the buyers and sellers to meet their energy requirement closer to real-time of operation. The introduction of real-time market will bring more flexibility in the market operations to provide real-time power balance while ensuring optimal utilization of the available surplus capacity in the system. Moreover, the RTM would help to mitigate challenges to the grid management due to intermittent and variable nature of renewable energy generation and therefore, help to integrate higher quantum of renewable energy resources into the grid. This half-hourly market will enable intra-day trade of electricity, allowing adjustment of generation and consumption profile during the day. Another impact of the COVID-19 pandemic on the power sector is in terms of the market dynamic. It can be observed that there is a dip in the clearing volume and the Market Clearing

Price (MCP), which coincides with the gradually increasing shutdown measures taken by the government as a response to COVID-19. Thus, the reduction in demand due to the lockdown is reflected in the volumes traded on the electricity market and the clearing price. The average market clearing price during management of COVID-19 in comparison to 2019 is shown in Fig. 4. It is noted that market clearing price is declined by 21% during lockdown period. During the lockdown period, the lowest MCP is 1.952 Rs./KWhr recorded on 25th March 2020.

Management of such large scale demand variation and unplanned demand-supply can be met with flexible generation sources to ensure grid reliability. As part of voltage control measures, all reactors were kept in service wherever required. Also, STATCOM and SVC were put in voltage control mode and capacitor banks at distribution level was kept off to maintain nominal voltage.

In this paper, looking into the adverse effects of variation in the load demand, an analysis is carried out on Indian electrical distribution system for such events in the future.

3. MODAL ANALYSIS

Voltage stability analysis using eigenvalues is known as modal analysis. Detailed modal analysis is presented to compute voltage stability of load buses [2]. Eigenvalues closer to zero indicate the presence of voltage collapse point in the vicinity of the present operating point. The static voltage stability analysis is based on modal analysis of the power flow Jacobian matrix as expressed in equation (1).

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta|V|\end{bmatrix} \tag{1}$$

Jacobian matrix $[J]$ is reduced to $[J_R]$ by substituting $\Delta P = 0$, where $[J_R]$ is reduced Jacobian matrix.

We can write from equation (1),

$$[\Delta Q] = [J_R]\Delta|V| \tag{2}$$

$$[J_R] = [J_4] - [J_3]\,[J_1]^{-1}\,[J_2] \tag{3}$$

From equation (3),

$$[\Delta|V|] = [J_R]^{-1}\,[\Delta Q] \tag{4}$$

Voltage stability characteristics of load buses can be assessed by computing eigenvalues and eigenvectors of reduced Jacobian matrix.

$$[J_R] = [\xi][\lambda][\eta] \tag{5}$$

$[\xi]$ is right eigen vector, $[\lambda]$ is diagonal eigenvector and $[\eta]$ is left eigenvector of $[J_R]$.

Combining equations (4) and (5).

$$\Delta[|V|] = [\xi][\lambda]^{-1}[\eta]\,[\Delta Q] \tag{6}$$

$$[\Delta|V|] = \left[\sum_i \frac{\xi_i\eta_i}{\lambda_i}\Delta Q\right] \tag{7}$$

Stable operation of the system can be judged by V-Q sensitivity. The bus with high V-Q sensitivity is vulnerable to voltage collapse. V-Q sensitivity at ith load bus is given by equation (8).

$$\frac{d|V_i|}{dQ_i} = [J_R]^{-1}{}_{ii} = \sum_i \frac{\xi_i\eta_i}{\lambda_i} \tag{8}$$

Bus participation factor and branch participation factors is given by equations (9)-(10). Bus with high participation factor is the most critical bus. Similarly, branch with high participation factor is the most critical line.

$$P_{ki} = \xi_{ki}\eta_{ik} \tag{9}$$

$$PL_{ij} = \frac{\Delta Qloss_{ij}}{\max(\Delta Qloss_{ij})} \tag{10}$$

Working steps are described below for the proposed work:

Step 1: Read the system line and load data.

Step 2: Perform load flow analysis and observe voltage profile and power losses in the system.

Step 3: Execute continuous power flow analysis and draw PV and QV curves to estimate loadability limits. Find critical bus and line using modal analysis.

Step 4: Install D-Statcom for total power loss minimization and voltage stability margin enhancement.

Step 5: Read the system line and reduced load demand profile during COVID-19 lockdown.

Step 6: Perform load flow analysis and observe voltage profile and power losses in the system. As part of voltage control measures, all reactors were kept in service wherever required. Also, STATCOM and SVC were put in voltage control mode and capacitor banks at distribution level was kept off to maintain nominal voltage.

Step 7: Repeat Step 3. And deploy D-Statcom for voltage control and voltage stability margin enhancement.

Step 8: Display voltage, total power loss, critical bus and line, voltage stability margin, D-Statcom rating.

Step 9: Stop.

4. RESULTS AND DISCUSSIONS

The analysis has been carried out on practically existing 33-bus, 100 MVA, 22 KV, Indian distribution system as shown in Fig. 5. Load demand on the test system before and during COVID-19 is illustrated in Fig. 6. Under normal operating scenario, load on the system is 16.2+j*11.2 MVA and due to lockdown, the power consumption is reduced to 8+j*5.6 MVA. PV and QV curves have been obtained at each bus to demonstrate real and reactive power margin values.

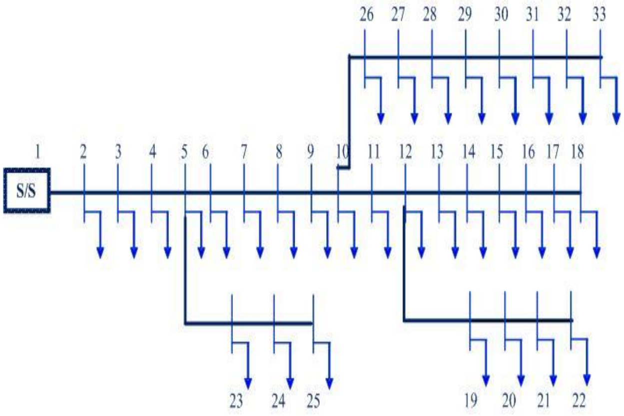

Figure 5. Single line diagram of 33-bus test system

In this paper, following three case studies are investigated, Case-1: Before COVID-19, Case-2: During COVID-19 lockdown without compensation, Case-3: During COVID-19 lockdown with D-STATCOM (voltage control mode). Modal analysis has been carried out for finding the critical buses and lines for the deployment of reactive compensation.

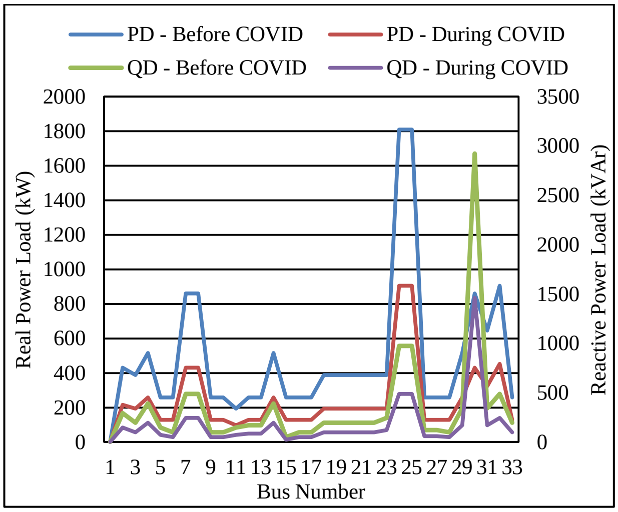

Figure 6. Load profile before and during COVID

A. *Case-1: Before COVID*

Voltage profile is shown in Fig. 7 and summary of results is given in Table I for all the three cases. It is recorded that, lowest voltage of the system is 0.8654 p.u which is violating the permissible limits. Further, complex line loss in the system is 1.4777+j*0.9868 MVA. In other words, 9.12% of total power is wasted in form of real and reactive power line losses. To manage voltage profile as per Indian Electricity Grid Code band and reduce energy loss, the system operator has installed capacitor banks at 30th, 24th and 10th nodes. After reactive power compensation with capacitor banks, lowest system voltage is improved to 0.90734 p.u and power loss is reduced to 0.853+j*0.572 MVA.

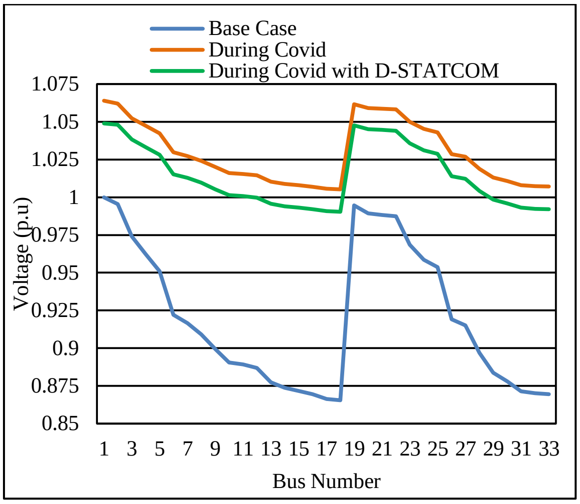

Figure 7. Voltage profile before and during COVID

PV and QV curves at each node in case-1 is depicted in Figs. 8-9. It is observed from PV curve that real power margin is low for 18th bus and it is the most critical bus. Similarly, 18th bus is having least reactive power margin and it is the most critical bus. Real and reactive power margin at critical bus are given in Table I. Modal analysis also performed and noted that minimum eigenvalues of J_R matrix is 0.0691. Bus participation and line participation factors are determined to identify weak buses and lines. Figures 10-11 represents bus and line participation factors for all cases and observed that at bus 18th is having highest participation factor value and is most sensitive bus to voltage instability. Branch 5th is having highest participation factor value and is most sensitive line.

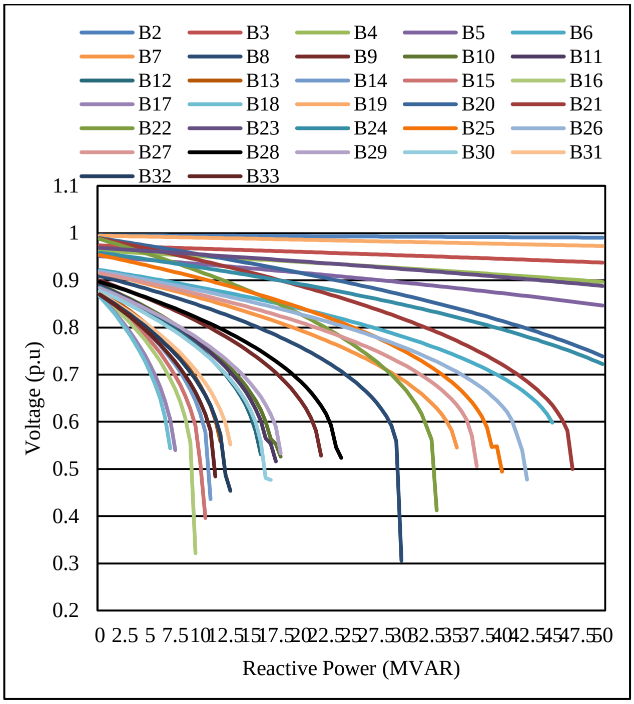

Figure 8. Q-V curve in Case-1

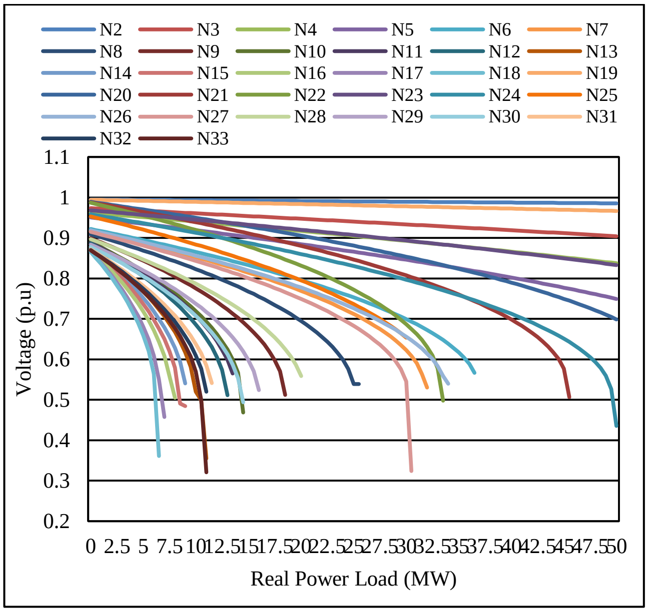

Figure 9. P-V curve in Case-1

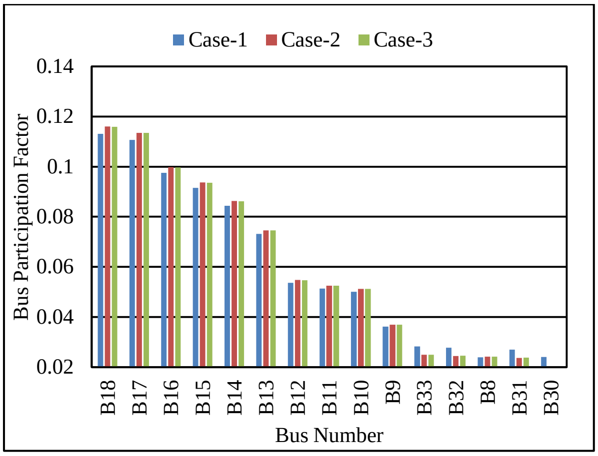

Figure 10. Bus participation factors

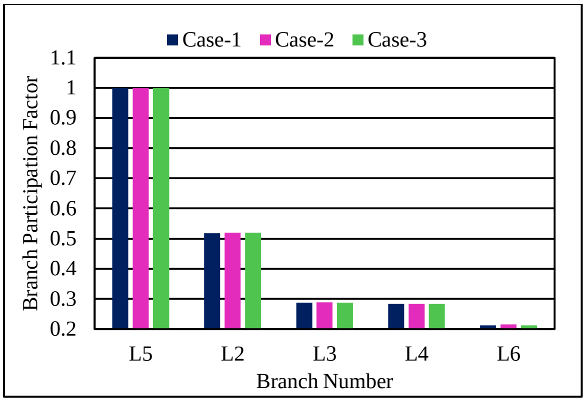

Figure 11. Branch participation factors

B. *Case-2: During COVID without Compensation*

As shown in Figure 7, voltage in Case-2 is beyond permissible range particularly at nodes 1, 2, 3, 19, 20, 21, 22 and 23. It is observed that, lowest voltage of the system is 1.0052 p.u and highest system voltage is 1.064 p.u which is violating the permissible range of 0.95 p.u – 1.05 p.u. Further, real and reactive power loss in the system is reduced to 0.2851+j*0.19 MVA compared to Case-1. Capacitor banks are switched off in case-2 and case-3 to maintain voltage at nominal value. PV and QV curves at each node in case-2 is depicted in Figs. 12-13. It is observed from PV and QV curves that real and reactive power margins are minimum at 18th bus and it is selected as the most critical bus. Modal analysis also performed and noted that minimum eigenvalues of J_R matrix is 0.0793.

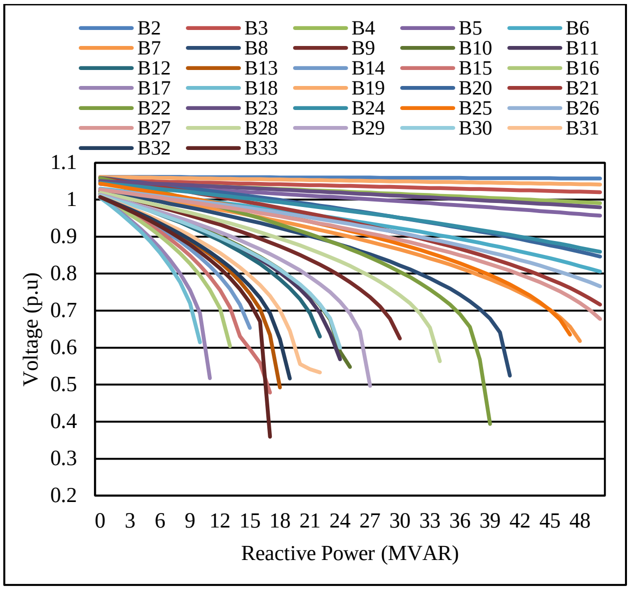

Figure 12. Q-V curve in Case-2

TABLE I. SUMMARY OF RESULTS BEFORE AND DURING COVID-19

Description	Case-1	Case-2	Case-3
Lowest Voltage (p.u)	0.8654	1.0052	0.9904
Maximum Voltage (p.u)	1.0	1.064	1.049
TPL (MW)	1.4777	0.2851	0.2935
TQL (MVAr)	0.9868	0.19	0.1956
D-STATCOM Rating (MVAR)	---	---	± 6
Real Power Margin (MW) at 18th Bus	6	10	9
Reactive Power Margin (MVAr) at 18th Bus	7	10	11

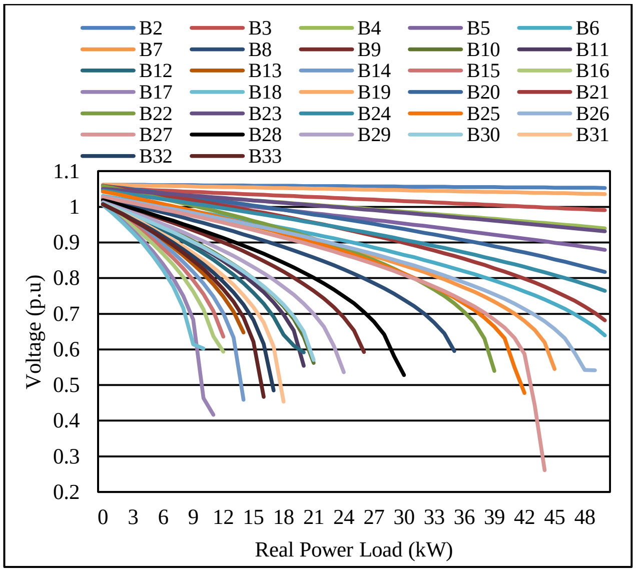

Figure 13. P-V curve in Case-2

C. *Case-3: During COVID with D-STATCOM*

To control the voltage, fast acting reactive power compensating device D-STATCOM is installed as shown in Fig. 14. D-STATCOM has the capability to operate in both the capacitive and inductive modes to control voltage under high load and light load conditions respectively. It is observed that, lowest voltage of the system is 0.9904 p.u and highest system voltage is 1.049 p.u which is within the permissible range. PV and QV curves at each node in case-1 is depicted in Figs. 15-16. It is observed from PV curve that real power margin is low for 18th bus and it is the most critical bus. Similarly, 18th bus is having least reactive power margin and it is the most critical bus. Modal analysis also performed and noted that minimum eigenvalues of J_R matrix is 0.084. V-Q sensitivities for the test system is shown in Figure 17.

TABLE II. COMPARISON OF RESULTS FOR D-STATCOM PLACEMENT FOR CASE-1

Description	w/o D-STATCOM	Proposed	PSI [27]
Lowest Voltage (p.u)	0.8654	0.8782	0.8723
TPL (MW)	1.4777	1.291	1.388
TQL (MVAr)	0.9868	0.884	0.944
D-STATCOM Rating (MVAr)	---	2.473	3.643
D-STATCOM Location	---	18th bus	25th bus

Further comparison of results for D-STATCOM placement for total power loss minimization is given in Table II. From Table II, it is noted that proposed method gives better results compared to other technique [27]. With the proposed method total power loss is reduced by 12.6 %.

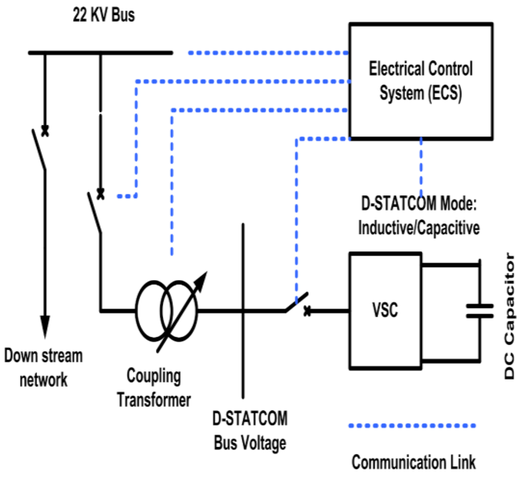

Figure 14. Typical representation of D-STATCOM

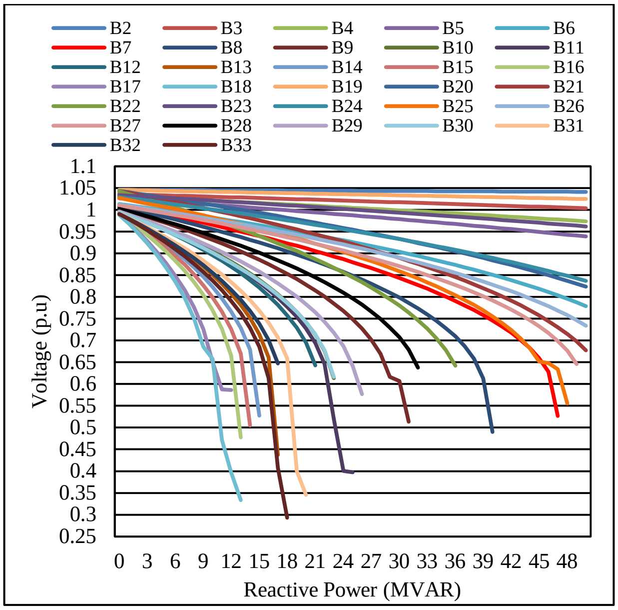

Figure 15. Q-V curve in Case-3

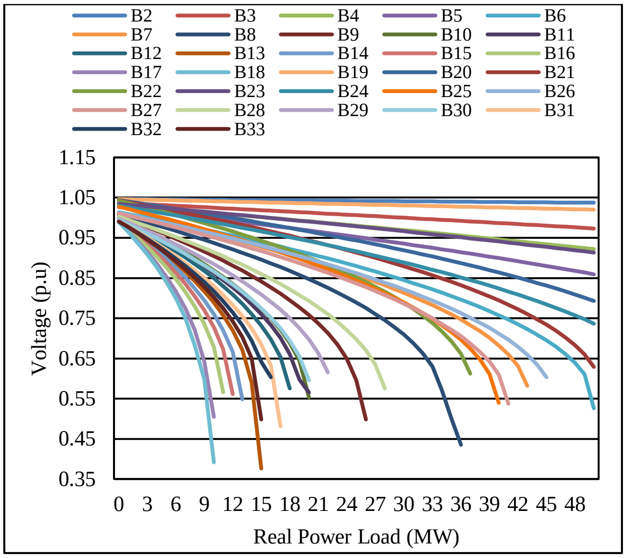

Figure 16. P-V curve in Case-3

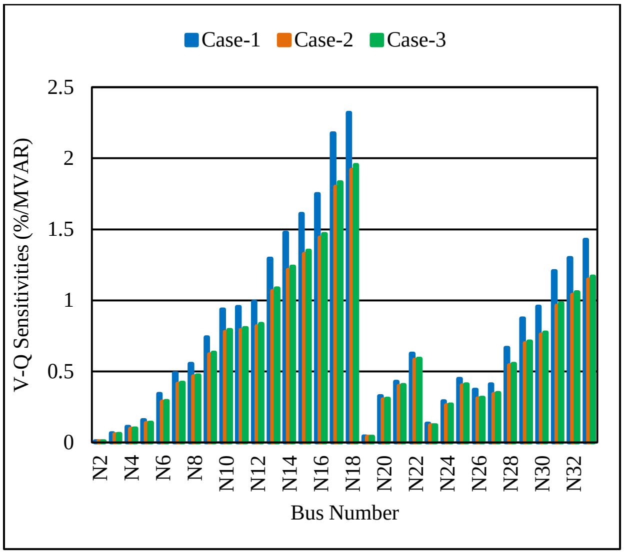

Figure 17. V-Q sensitivities

5. CONCLUSIONS

Power consumption had declined following the COVID-19 outbreak as economic activity came to a standstill due to the lockdown. Consequently, increase in residential load demand is observed as employees are working from home and people are restricted to home. Management of such large scale demand variation and unplanned demand-supply can be met with flexible generation sources to ensure grid reliability. Appropriate voltage control measures shall be planned taking into account of such large variations in load demand due to unprecedented global pandemic like COVID-19. In this paper, looking into the adverse effects of variation in the load demand, an analysis is carried out on Indian electrical distribution system for such events in the future.

In this paper, voltage security problem is studied under uncertain steep fall in power consumption due to lockdown in wake of COVID-19 pandemic. P-V and Q-V curves are plotted at each node using continuous power flow approach to find maximum loadability limits. The bus with least loadability limit is considered as weak bus. Further, modal analysis also performed on the test system to find minimum eigenvalue of reduced Jacobian matrix. Moreover, bus and line participation factors are calculated to identify sensitive bus and line. It is noted that during the lockdown period, voltage profile in the test system is beyond the permissible range. The simulation results shows that voltage profile is managed as per IEGC requirements with D-STATCOM placement. Based on comparison of results it is noted that the proposed D-STATCOM installation provided better results of loss reduction and voltage profile improvement.

The challenges of global pandemics provide opportunity to the network operators to develop resilient electricity system and strengthen the power system with flexible generation, efficient grid planning, accelerate demand-side management, Volt-Var control, distributed energy resources and energy storage systems.

The analysis will be helpful to network operator for effective reactive power management and planning for adequate reactive power margin to ensure grid reliability under unexpected situations like COVID-19 pandemic.

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Dr. V.V.S.N. Murty Vallem received his B.Tech in Electrical Engineering from Jawaharlal Nehru Technological University Pulivendula in 2010, M.Tech and Ph.D. in Power Systems from National Institute of Technology, Kurukshetra in 2013 and 2020. He is working as Manager in Electrical Department at Engineers India Limited, New Delhi. His research interest is DG and D-FACTS integration in distribution system, reactive power management, voltage control, energy management and micro grids. He is a member of International Association of Engineers (IAENG) and Associate Member of International Association of Outsourcing Professionals (IAOP). He is editorial board member of American Journal of Electrical Power and Energy Systems and Lattice Science Publication. He received prestigious POSOCO Power System Award (PPSA) for best thesis on all India level. He has three book chapters and 30 research publications in various reputed international Journals and Conferences.

Dr. Ashwani Kumar is presently working as HOD & Professor in the Department of Electrical Engineering at NIT-Kurukshetra, Haryana. He received his B.Tech in Electrical Engineering from Pant Nagar University in 1988 and Master degree in Power Systems from Panjab University, Chandigarh in 1994 in honors. He received his Ph.D. from Indian Institute of Technology-Kanpur in 2003. He did Post-Doctoral from Tennessee Technological University, USA. He has started collaboration with academic Institutions / R&D Labs including IIT Kanpur and Delft Uni. Netherlands for the project work in the area of Smart Grids. He has executed three research project sponsored by different funding agencies including DST, AICTE etc. He has also carried out few consultancies assignments for power companies. His research interest includes Power Systems, Power Systems restructuring, Transfer capability assessment, congestion management, Demand side management, distributed generation integration, Reactive power management and Ancillary services, Transmission and distribution pricing. He has more than 100 publications in the journals of repute including IEEE Trans. on Power Systems, IET-GTD, Elsevier, Taylor and Francis, Springer, Berkeley, Emerald, JES, IEI series B etc. He has guided 11 Ph.D and more than 40 M.Tech research theses. Eight of his research students have been awarded with prestigious POSOCO Power System Award (PPSA) for best thesis on all India level.