International Journal of Electronics Engineering (ISSN: 0973-7383)
Volume 11 • Issue 1 pp. 479-488 Jan 2019-June 2019 www.csjournals.com

Improving Voltage Stability through Demand Side Load Management

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Abstract: Power systems cater to continuously varying loads. These varying loads, on rise, during grid peak hours, can throw generation to the verge of breach of capacity, leading to voltage instability and further complications. Usually during peak hours of the grid, sequence of events to happen is loss of quality of power → loss of stability → system collapse. The peak time load shedding is an established practice for mitigating the risk of voltage instability. Traditional load shedding is indiscriminate withdrawl of energy supply, of distribution circuits, and is quite unwelcome for the consumers. This situation can be dealt, better with consumer himself surrendering identified differable loads in his premises, to the utility, for rescheduling during times of distress and thwarting the possible load shedding. This paper proposes a fuzzy logic baseddemand side load management scheme for improvement in voltage stability, during peak load hours, of a particularly high demand season; the stressed season. The scheme employs fuzzy logic principles to effectan indirect control of deferrable loads in consumer premises. The scheme tries to extract a reactive power reserve, during peak hours to help the system fend off instability. The proposed demand side load management works for change in time of useof deferrable loads, based on forcast of system state. These deferrable loads include heating ventilation, air conditioning (HVAC), battery charging etc., typically. The authors have used modelling and simulation to assess performance of the scheme. The study is done for a bus catering to a group of typical domestic consumers. The simulation results show remarkable dropinpower drawn from grid during peak hour in range of 7.5% to 23% for adaptation of scheme. The study is conducted for three states of the power system; "alert", "emergency", and "In-extremis".
Keywords: Fuzzy logic control, Demand side load management, Voltage stability, Peak management, Reactivepower management.

1. Introduction

Power systems around the world struggle with continuouslyvarying power demand. Variations in demand challenge economic generation on one hand and raise risk of instability on the other. A major concern for utilities is voltage stability of system, owing to operation of the system at the verge and breach of capacity. Loss of voltage stability means unacceptable lower levels of bus voltage and subsequent collapse of grid. Voltage instability cost millions of dollars to the utilities every year [1]. The voltage instability is attributed to system's inability to supply additional reactive power during peak hours [2].

Demand-Side Management (DSM) has helped utilities for long, in management of power delivery, and maintaining health of power systems. Anaptly designed DSM program can reduce cost of energy for utilities, and is an accepted technique, for load management [3]. DSM has many strategies, includes efficient utilization, improved installation, and peak management etc.. The demand side load management (DSLM) is one of the DSM techniques, which is implemented inside consumer premises, invoking consumer cooperation. It is targeted at selection, and optimization in operation of appliances. Power systems operate mainly in two seasons. 'Relaxed seasons'; when total generation capacity available is greater than the peak demand, and a 'Stressed seasons' when total generation capacity available is barely enough to meet peak demand. The power-voltage curve (PV)[4] margins have long been accepted as an indicator for voltage stability. ONS (Brazilian System Operator) studies recommended a minimum PV margin requirement of 6% considering simple contingencies [5]. The Western ElectricityCoordinating Council (WECC)proposed a minimum PV margin requirement of 5% considering simple contingencies, 2.5% for double contingencies, and larger than zero for multiple contingencies [6].

Change in TOU of equipment, inside the consumer premises, if implemented with an objective of bringing down the total injected power into the grid, during periods of an expected exigency, can save the utility fromaneventual decision of load shedding. An appropriate change in TOU of equipment during peak hour can reduce the maximum energy demand [7]. The peak hour load managementfor stressed season, proposed here,aims to mitigate risk of voltage instability by bringing down reactive power (inductive)injected by consumers into the bus. Smart meters or advanced metering infrastructure (AMI) communicates with grid ICT in real time, and shares energy consumption and other demand response signals. We used the data available with AMI for demand side load management (DSLM) inside consumers' premises. This work asks consumer to define deferrable loads (D-loads) inside his premises, whose operation when delayed or advanced by a finite time, doesn't affect consumer comfort.These D-loads are surrendered to an automatic scheduler.Identification of defferable loads is a common option used by DSLM schemes for active power management scheme, such as load profile smoothing[8].This scheduler, during events of emergency, defined by utility, reschedules plug-in time of D-loads.Thishelpsreducethe mean reactive power injected into the grid, during peak hour, by the consumer. When, a DSLM of the sort is implemented on number of consumers serviced by a bus, the grid stability can be improved. Contributions of this work includes:

a) To formulate a DSLM for improving voltage stability, using fuzzy principles.
b) To assess the performance of this DSLM for improvement in voltage stability
c) To establish efficacy of this DSLM for improving voltage stability, of the system.

Theproposed DSLM system utilizes principles of fuzzy logic to compute rescheduled plug-in time of appliances, during grid peak hour of stressed seasons. The parameters chosen for evaluation of efficacy of the scheme are: drop in re-active power and apparent power injected into the bus by group of consumers, and two indexes: line voltage stability index, and voltage collapse proximity index measured at the bus. The presented work extends a work [9] which was published as a work-in-progress.

2. The Problem

Energy demand on a power system varies with time, for intermittent tapping of energy from the grid, driven by consumers' motives, in desired volumes, at desired time. Voltage and frequency, are good indicators of stability of a power system. The power systems are seen to be operating in a particular state, based on some inequalities (limitations of physical equipment, such as maximum currents and voltages) and some equalities (balance of active and reactive power at each node) are complied with or not (fig. 1). The system state is 'Normal' if theseare complied. The system goes into state 'Alert' if it is at the verge of breaching the equalities/ inequalities and calls for observation and actions such as generation shifting andlikepreventive measures to restore to 'Normal'.The system may move from 'Normal' or 'Alert' to a worse state, 'Emergency', if disturbances are severe, and some inequalities are breached. This state necessitates acts like, load shedding or invoking of additional capacities to revert to 'Alert' or 'Normal'. If equalities are also breached, the system move to the severest state 'In-extremis'. The system state 'In-extremis' leads to partial or complete collapse of grid. The first response, to this situation is directed at limiting damage, restrict proliferationof collapse by isolating faulty part of the system from healthy. This state, when resolved, moves to 'Restorative' state. In restorative state, the part of system isolated in 'In-extremis', is reclaimed and system is restored to 'Normal' or 'Alert'. These states of a system are indicative of different levels of severity [4].

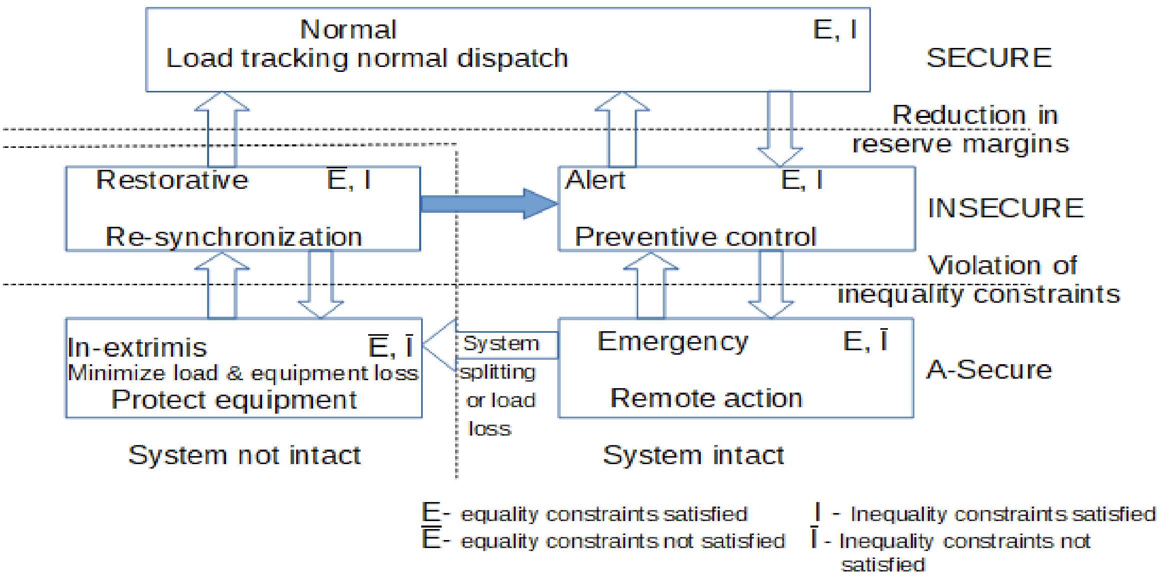

Figure1. States of a power system [4]

Now, let us look at different power system components. The generation, deploys synchronous generators invariably, whereas loads keep varying with time, with varying power factor. Generation and loads are connected by transmission/ distribution lines, and transformers. The loads consume active and reactivepower, and thetransmission/ distribution network consumes mostly reactive power.To understandvoltage stability concerns of a power system, let us look at a lumped component model forpower system (figure-2).

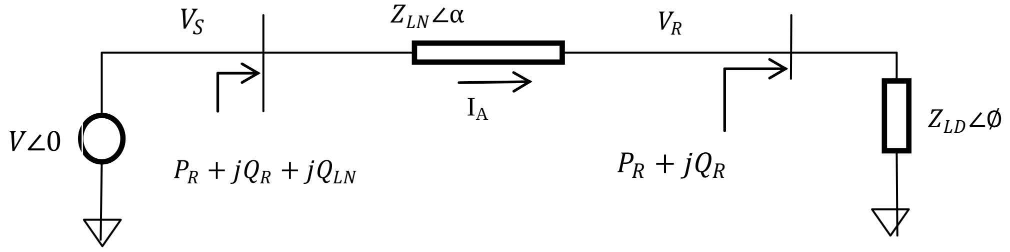

Figure2. Simplified representation of power system

It has an a.c. source, $V\angle 0$ (representing generation), connected to a load impedance, $Z_{LD}\angle\phi$, through a series impedance $Z_{LN}\angle\alpha$ representing transmission. The magnitude of current 'I_A' is

$$|I_A| = \frac{V}{\sqrt{(Z_{LN}\cos\alpha + Z_{LD}\cos\phi)^2 + (Z_{LN}\sin\alpha + Z_{LD}\sin\phi)^2}} \qquad (1)$$

Magnitude of receiving end voltage V_R is

$$|V_R| = \sqrt{((V - I_A Z_{LN}\cos\alpha)^2 + (I_A Z_{LN}\sin\alpha)^2)} \qquad (2)$$

$$\vec{V}_R = \vec{Z}_{LD}\vec{I}_A \qquad (3)$$

Receiving end active power 'P_R' is

$$P_R = V_R I_A \cos\phi \qquad (4)$$

Receiving end reactive power, 'Q_R' is

$$Q_R = V_R I_A \sin\phi \qquad (5)$$

The two terminal network representing power system here, assumes that under steady state the generator terminal voltage 'V' is maintained constantthrough field excitation control. The line impedance Z_{LN} is mostly inductive with Tan(α) nearing 10, and is assumed to be constant. The load impedance Z_{LD} is assumed to be lumped at the bus. The load impedance varies continuously with time, as consumer appliances keep plugging-in and plugging-out. As the demand increase, Z_{LD} drops, $|I_A|$increases. Eqn. (1) suggests that any drop in Z_{LD}, leads to a rise in $|I_A|$, which in turn, increases voltage drop across Z_{LN}, causing a drop in $|V_R|$. The generation tries to bring V_R, back to an acceptable level, by exercising excitation control, increasing V,

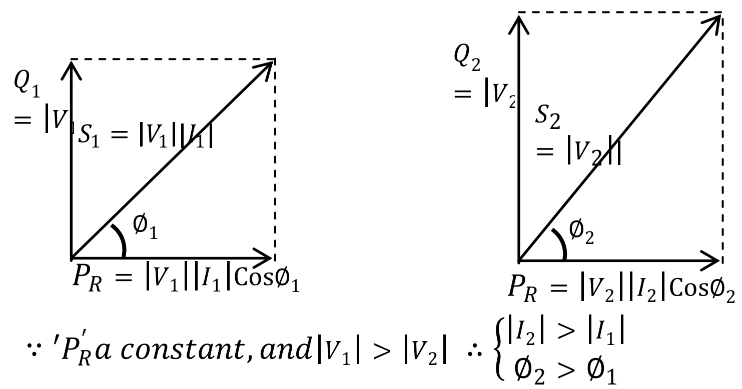

Figure3. Power triangles at load bus for constant power load

if excitation current limit is not breached. In case this limit is breached, excitation no longer push V up, and V_R drops, to attain a lower equilibrium value, decided by V.The loads in consumer premises are mostly defined-power type, which means, a drop in terminal voltage will ensue, a rise in current |I| and 'ϕ' to keep P_R, $|V|.|I_A|.Cos\phi$, (active power) constant (Fig. 3.). This leads to an increase in apparent power 'S_R', $|V_R|.|I_A|$, and reactivepower, Q_R, $|V|.|I_A|.Sin\phi$. Here, 'Cosϕ' is power factor of the load. Any drop in bus voltage for a defined power load, leads to a higher reactive power injection into the grid.

The reactive power demand is met either by generation through field excitation control or by grid side compensation- including switched capacitor banks, and active VAR compensators. Reactive power compensation in distribution network is done through distributed generatorsoperated as synchronous capacitors[10]. Grid side compensation provides bulk reactive power injection, helping steady state reactive power compensation. These are located across the network, near consumers; the traverse of reactive power through network is planned short, thus reducing further deterioration in bus voltage. The generation side reactive power injection through field excitation control is a precise response, but reactive power being injected, traverse through the network, and leads to further voltage drop along Z_{LN}.

Fig. 4. shows the phasors at generation; for generator delivering lagging power factor, unity power factor, and leading power factor. As bus voltage drops, excitation control at generation increases field excitation and pushes generated e. m. f. 'E' up. The magnitude of 'E' is proportional to the field excitation over range of operation. Here jX_S is the synchronous reactance and 'R_A' the internal resistance, of the generator, 'δ' is power angle and 'θ' phase of armature current 'I_A' w.r.t. terminal voltage 'V' of the generator. We see in fig. 4., reactive power ($|V|.|I_A|.\text{Sin}\theta$) by the generator to the grid, depends on field excitation. An over-excited generator delivers lagging reactive power, a critical excited, delivers pure active power (0 reactivepower), and under-excited delivers leading reactive power. The maximum reactive power

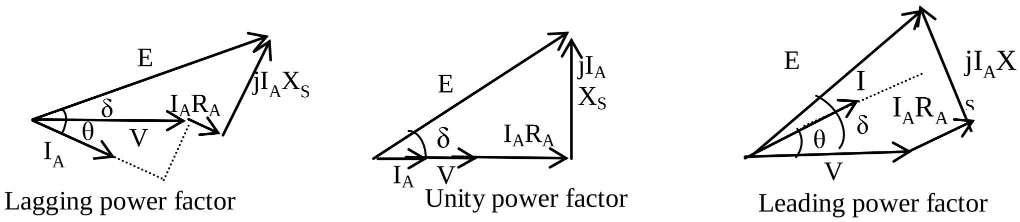

Figure4. Phasor Diagrams for a synchronous generator

which can be supplied by the generator is limited by the field current. During operation in 'alert' state of the system, for an incremental demand Q_R if the excitation current limit is breached, and generated e.m.f.attains saturation, then armature current increases to make up for the reactive power demand. This increase in I_A causes drop in V_R, and the bus settles at a lower operating voltage. As Q_R demand keeps increasing I_A, continues to rise, V_R continues to drop and keeps settling at lower V_R values. Once V_R drops to breach of inequality, the system enters 'Emergency' state. The region of operation where the grid is able to settle at some lower V_R, for any incremental demand of Q_R, is considered stable. At some critical Q_R demand, any further rise in demand of Q_R the generation attains armature current limit, and Q_R goes uncompensated, drop in V_R continues unabashed, and this leads to grid voltage collapse, a condition termed as voltage instability. Here, the system enters 'In-extremis' state. In this state the system needs to be saved; islanding, and other restorative activities help. Systems are likely to succumb to voltage instability during grid peak hours, in seasons of stressed operation[11].The generators have an inherent reactive power reserve, that is invoked during grid peak hour if Q_R demand rise. This Q reserve is available at the cost of active power generation capability and is vital for system's capability to cope-up with disturbances, and it must be preserved.

3. The DSLM framework

The DSLM system requires a hardware infrastructure, facilitating information exchange, between nodes, database management, carrying out computations and deriving control for switch gears. The DSLM system

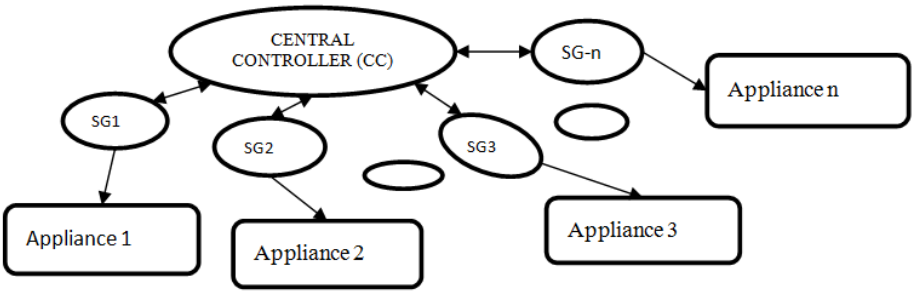

Figure5. Conceptual DSLM framework

operates inside each consumer's premises.Architecture of DSLM system is inspired by that proposed in a paper by the author [12]. The ICT framework for DSLM system has a central controller (CC), a database manager cum processor module. It maintains database, analyze data, runs algorithms to derive and deliver instructions to individual switchgears, and control respective switchgears, if desiredso. The smart switchgears are preceded by a switchgear interface (SG) which has current, voltage, and p.f. transducers, with appropriate analog to digital conversion, and transceiver module. The SG can make or break electrical connection to appliance, which it controls, manually or electrically through instructions it receives from CC. The transceiver of SG continuously transmits current and voltage to CC and receives instructions for switchgear concerned. SG has LEDs mounted on its front panel as flags (for visual communication to the users). The CC has datalinks with AMI and all SGs. It maintains database of active load drawn (LD) from the mains, power factor (pf), plug-in time (ST), plug-out time (ET), etc., for each appliance, in the network. The AMI shares information with CC like forecast for state of the power system,grid peak hour etc.for the day. The CC maps state of the power system to severity ‘μ’, as 0 for ‘normal’, 1 for ‘alert’, 2 for ‘emergency’, and 3 for ‘in-extremis’.

The nodes are identified by their unique identifiers, deferrable or non-deferrable in DSLM communication. The DSLM has two modes of operation: training mode and functional. During training mode, DSLM is run for a significant number of days, to allow CC build a primary database for nodes. During this period CC does not release instructions to nodes and simply access data from appliances. The CC, then analyses database of LD, pf, ET, ST, etc. for all nodes, to extract earliest start time (EST), latest start time (LST), mean operation time (OT), load in KVA, KVAR etc. for each node.These initial EST, LST, OT, etc. are used as input to an algorithm, for computation of correction in plug-in time for different nodes. The CC keeps updating EST, LST etc.. The AMI shares forecast for the day start time of peak hour ‘S’, end time of peak hour ‘E’, and state of the system with CC.Next it enters into functional mode.

4. The algorithm

The CC fetch data from AMI, well ahead of the start of peak hour of the grid. The CC maintaining databases of different nodes creates revised schedule of start time for the D- loadnodes. This leads to desired change in loading of the grid during peak hour, by the consumer. A DSLM is more acceptable to consumers if it accomodates consumer comfort as a primary constraint. This DSLM, has accorded consumer comfort, a high priority.

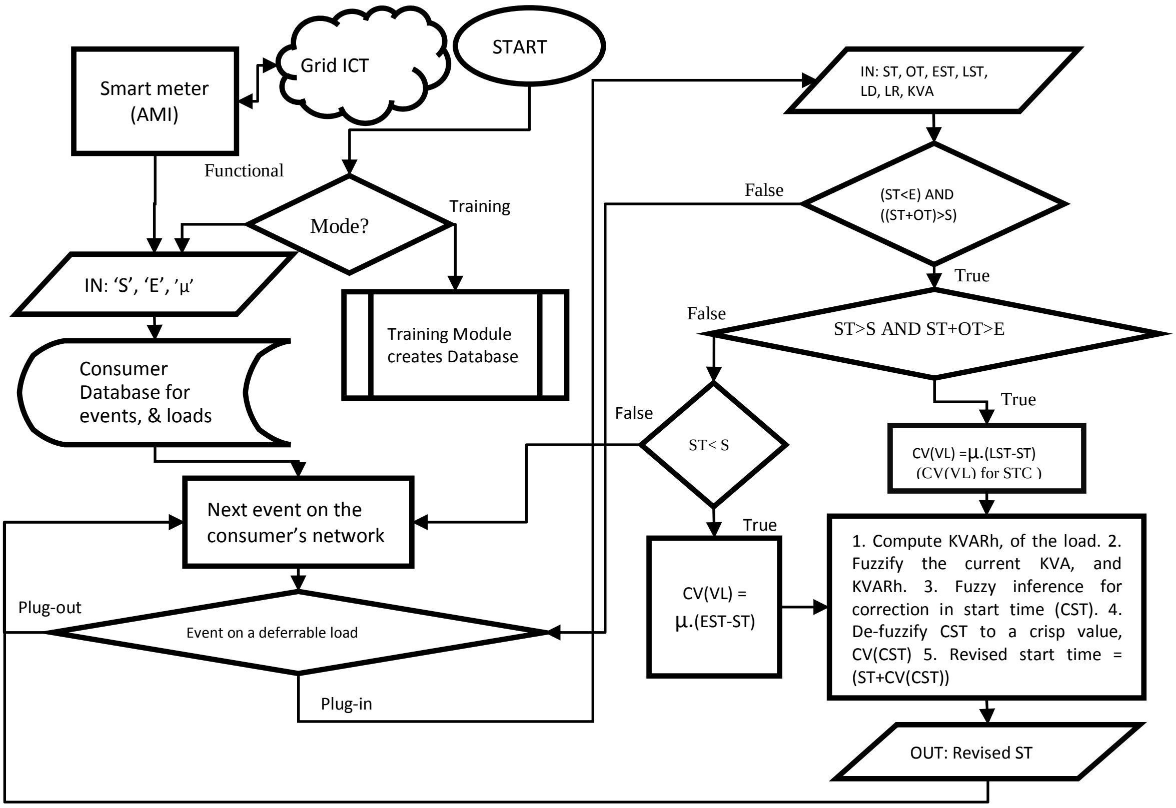

Figure 6. Flow chart for algorithm

This DSLM acts only on plug-in time of an appliance. Also, the consumer’s apparent power consumption is considered while defining shift in plug-in time of an appliance. The D-loads once plugged-in either by consumer or CC, are not interrupted by the CC.The CC computes total connected active load and reactive load, on a real time basis. Under instructions of utility (through AMI, μ > 0), it can effect change in TOU, for different D-load nodes. The plug-in time of a D-load can be advanced or delayed. The algorithm is presented as a flow chart in fig. 6.

The decision regarding amount of time by which plug-in time, of a given D-load to be shifted, is made dependent on KVARh of the D-load concerned, and expected KVA loading of the consumer, at the time of plug-in. Here KVARh of the load is product of KVAR and OT of the D-load. The two parameters KVA loading of consumer and KVARh of the D-load areexpressedin notional terms, used as input to fuzzy engine

A. Fuzzification

Fuzzification requires defining analog values or crisp values (CV) of input and output variables in terms of membership functions (MF), and associated grade of membership (GOM)[13]. The levels of KVA load of consumer, KVARh of the load, and shift in TOU are classified for 5 MFs, very small (VS), small (S), medium (M), large (L), and very large (VL). CV for membership functions of fuzzy levels is defined as (CV(x) is read as ‘crisp value of variable ‘x’’.):

CV(VS) for KVA: min. apparent load of the consumer for connected loads, for a similar day.

CV(VL) for KVA: max. apparent load of the consumer for connected loads, for a similar day.

CV(VS) for KVARh: minimum KVARh for all connected loads for a similar day.

CV(VL) for KVARh: maximum KVARh for all connected loads for a similar day.

CV(VS) for shift in start time of the node: 0

CV(VL) for shift of start time of the node, in case:

a. load is being advanced: µ.(EST-ST)
b. load is being delayed: µ.(LST-ST)

The effect of severity ‘µ’, (µ =1, for alert state, 2, emergency, 3 in-extremis) is accommodated in CV(VL). Accordingly shift in TOU will be scaled. The membership functions VS, S, M, L, and VL are equally spaced defined as,

$$\mathrm{CV(M)} = \frac{(\mathrm{CV(VL)}+\mathrm{CV(VS)})}{2} \quad (6)$$

$$\mathrm{CV(S)} = \frac{(\mathrm{CV(M)}+\mathrm{CV(VS)})}{2} \quad (7)$$

$$\mathrm{CV(L)} = \frac{(\mathrm{CV(VL)}+\mathrm{CV(M)})}{2} \quad (8)$$

Next, fuzzification requires us to define the membership function (MF), associated with these fuzzy levels. We use triangular MFs for these fuzzy variables. Fig. 7. explains triangular membership function. For example, crisp value associated with ‘x’ isdefined as ‘S’ with grade of membership (GOM) ‘P’, or ‘M’ with GOM ‘Q’. ‘P’ and ‘Q’ the GOMs for X with ‘S’, and ‘M’, respectively, can take value between 0 and 1.

The CC fuzzifies inputs, KVA of the consumer, at expected plug-in time of concerned load, and KVARh of the load. The determination of fuzzy sets, for the variables KVA and KVARh, require us to define the respective MFs with GOM. In the fig. 7. GOM for x, (x-x’) is defined, for membership ‘S’,

$$\mathrm{P} = \frac{(\mathrm{x} - \mathrm{CV(S)})}{(\mathrm{CV(M)}-\mathrm{CV(S)})} \quad (9)$$

and GOM of x, for ‘M’,

$$\mathrm{Q} = \frac{(\mathrm{CV(M)} - \mathrm{x})}{(\mathrm{CV(M)}-\mathrm{CV(S)})} \quad (10)$$

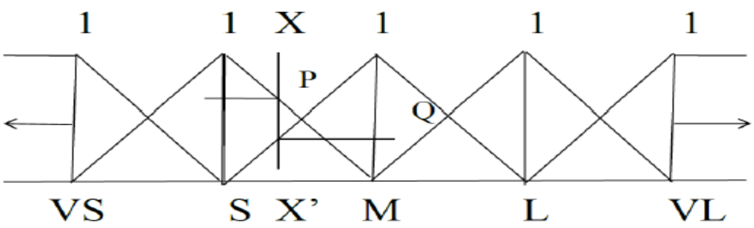

Figure7. Triangular membership functions

B. Fuzzy inference and De-fuzzification

Next, we define inference for different combinations of two fuzzy variablesKVA and KVARh. The table 1 defines inferences for shift in TOU, for load in terms of MFs. This table defines action for set of MFs, based on heuristics. We have used conjunction between the two variables.

Table 1.: Fuzzy inference for shift in TOU

KVA load of consumer	KVARh of the load				
	VS	S	M	L	VL
VS	**VS**	**VS**	**S**	**M**	**L**
S	**VS**	**S**	**M**	**L**	**L**
M	**S**	**S**	**L**	**VL**	**VL**
L	**S**	**M**	**VL**	**VL**	**VL**
VL	**L**	**L**	**VL**	**VL**	**VL**

For example, we read the inference S, as: when KVA loading of consumer is "Very Small -VS" AND KVARh of the load is "Medium – M" then the shift in plug-in time needs to be "Small - S". The GOM of time shift as per conjunctive association is Minimum (GOM (KVA), GOM (KVARh)). Once the inferences are defined, with respective GOMs, the next step is to derive CVs for quantum of shift in TOU, of the load through de-fuzzification.

CV of 'x' can be seen as 'S', or 'M', with GOMs P and Q respectively (fig. 7.). When we define two variables as fuzzy sets, we have two MFs, with associated GOMs for each variable. Here, GOMs for KVA, and KVARh are defined as per eqn. (9), and (10). The two variables each having two MFs, will lead to four conjunctions, for four pairs of MFs. The inferences are defined as in table-1. The crisp values are computed as suggested by Sugeno [14].

$$\mathrm{CV(Time\ Shift)} = \frac{\sum \mathrm{CV\,(MF_{\,i}).GOM_{\,i}}}{\sum \mathrm{GOM_{\,i}}} \qquad (11)$$

5. Modelling and simulation

The typical consumer for this study is an installation of 120 to 150 appliances, with power factor (p.f.) between 65% and 99%. These loads are considered as constant power loads. Some of these loads are categorized as D-loads, by the consumer. Examples for these deferrable loads are air-conditioning,ventilation, heating appliances, battery charging, water pumping etc.. These loads are being plugged-in at different instances of time during a typical day. An installation (consumer) can be seen as a collection of loads, with defined power consumption, active (LD) and reactive (LR). The load usually plug-in to the grid, at a typical time of the day (ST), and remains connected for a typical mean time (OT). The consumer is modelled as a time series of ST, LD, LR, and OT of various loads, with a defined distribution of collection of STs. The ST, LD, LR, and OT for different loads, of the representative consumer are extracted out of standard consumer data [15]. The ST, LD, LR, and OT for different loads, for the representative consumer, is taken as seed, and other consumers' data is generated with help of random number generators available in Microsoft Excel®.Modeling of consumers, and DSLM, and simulation of operations is done in VBA for Microsoft Excel®. The plug-in time for any given load shows variation over a number of days, from earliest start time (EST) to latest start time (LST). The EST and LST are used as reference for maximum shift in plug-in time, for advancing or delaying, respectively.

Simulation is performed for three system states, alert, emergency, and in-extremis by letting 'µ' take values 1, 2, and 3 respectively. This is an apt case for discrete event simulation. The events identified are, the plug-in time ('ST') and plug-out time (ST+OT)of a load, inside a consumer premises. It is assumed that the load does not vary between, plug-in and plug-out. The aggregate connected active, reactive, and apparent load for the consumer is computed at every event, during the day. These events along with aggregate connected load, defines the reactive, active, and apparent load profile of the consumer. For each run, simulator defines fuzzy sets for KVA, and KVARh, for the consumer, at every event. The simulator seeks user input for start time of peak hour of the grid (S), and end time of grid peak hour (E). The value of 'S' taken for this simulation is 15:30 hrs, and 'E' 18:30 hrs.. The simulator identifies D-loads operating during peak hour. Some of these loads may have their plug-in ST earlier to S, and plug-out between S and E. Their plug-in is advanced, so as to bring down the loading during peak hour. Similarly, the loads which have ST between S and E and plug-out beyond E, will have their ST delayed. The advancing or delaying plug-in is accommodated in definition of CV (VL) for time shift, in fuzzification step. The quantum of time shift is computed as per eqn. (11). Such simulations are performed on large number of consumers, having similar load profiles. We conducted this study for 300 consumers connected to the bus. Simulation for these consumers, pre and post application of correction is performed, and aggregate load profile is created for the bus. The bus voltage is computed, using eqn. (3) for various values of reactive and active power drawn from bus, at different events (consumer events become bus events).

The voltage stability assessment is done using line stability index (L_{mn}) [16], based on power transfer computations on single line π-model. Its value for a stable system should be greater than 0 and less than 1. A smaller value indicates a more stable system.

$$L_{mn} = \frac{4XQ_R}{(V_S \operatorname{Sin}(\theta-\delta))^2} \quad (12)$$

L_{mn} :Line stability index
V_S : Magnitude of sending end voltage
X : Effective reactance of the load measured at bus
θ :Effective impedance angle of the load measured at bus
δ : Power angle at sending end

Another voltage stability index we utilized is based on active power transferred across the line, voltage collapse proximity index (VCPI)[17]. It is defined as ratio of active power transferred across a line, to maximum active load transferrable across the line. It indicates a voltage stable system for values between 0, and 1.The two indexes are computed at all events, of the bus, and plotted against time. Comparison of values of these indexes, preand post-adaptation of DSLM, indicated improvement in voltage stability.

$$VCPI = \frac{P_R}{P_{Rmax}} \quad (13)$$

P_R: Active power drawn from the bus, at receiving end.
P_{Rmax}: Maximum active power, that can be transferred across the transmission line.

6. Results and analysis

The simulation results are discussed in order of forecast states of system (μ). Load profile, and voltage stability indexes, for pre and post adaptation, of DSLM, plotted, for forecast system states alert, emergency, and in-extremis.

A. System state forecast 'Alert':

Simulation results for system state "Alert",corresponding to severity μ=1 are shown in fig. 8 and fig. 9. The active load P in_p.u., and reactive load Qin_p.u., drawn from the bus droppped by about 4% and 5% respectively, for adaptation of DSLM, in fig. 8at grid peak time. In fig. 9 stability indices VCPI, and L_{mn} during grid peak hour, show betterment by 0.07, and 0.08at grid peak time, respectively.

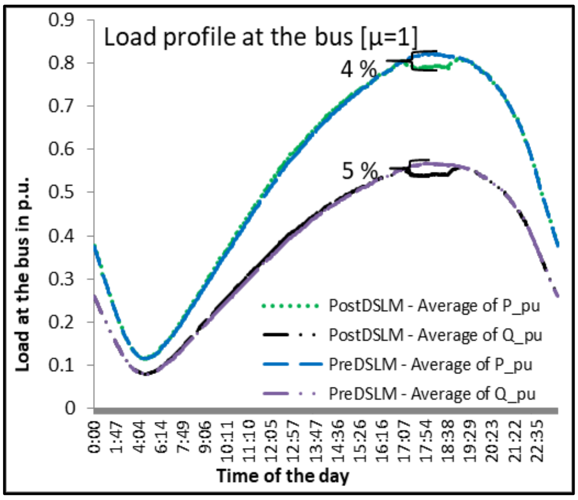

Figure 8. Active/ Reactive Load profile at bus, μ=1

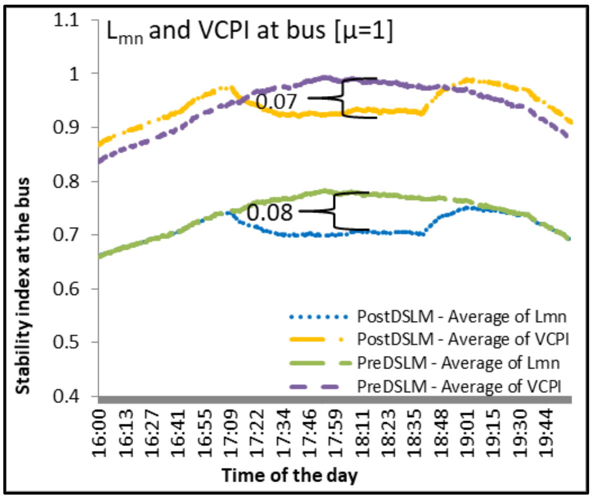

Figure 9.VCPI&L_{mn} at bus, during peak hour, μ=1

B:System state forecast 'Emergency':

Simulation results for system state “Emergency”, corresponding to severity μ=2 are shown in fig. 10.and fig. 11. In fig. 10, active load P in p.u. and the reactive load Q inp.u., drawn from the bus, dropped by about 7.5% and 9% at grid peak time, respectively. The stability indexes VCPI, and L_{mn} plots for grid peak hour, in fig. 11, show betterment by 0.14, and 0.15at grid peak time, respectively.

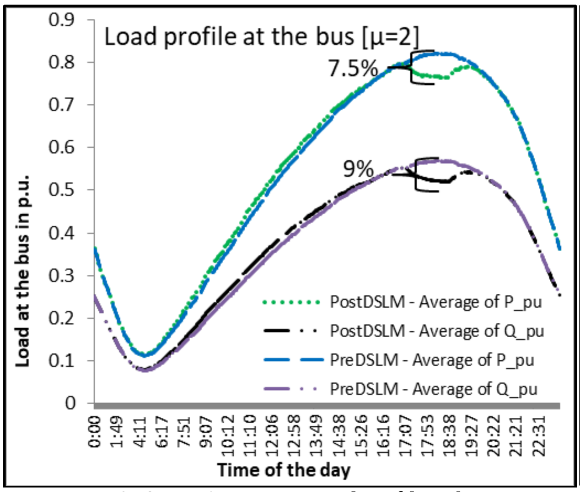

Figure 10. Active/ Reactive Load profile at bus, μ=2

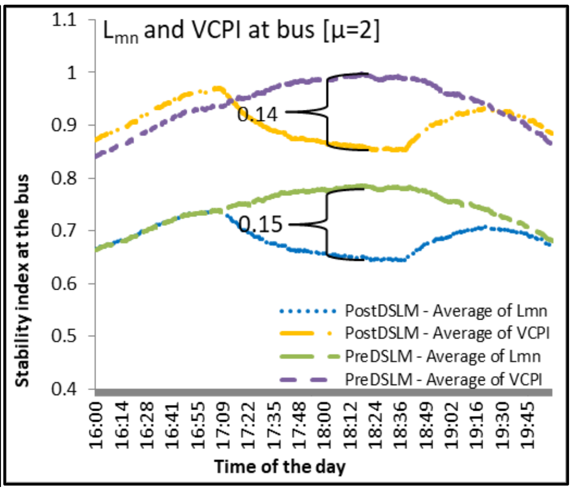

Figure 11. VCPI &L_{mn} at bus, during peak hour, μ=2

C. System state forecast ‘In-extremis’

Simulation results for system state “in-extremis”, corresponding to severity μ=3 are shown in fig. 12.and fig. 13. In fig. 12, active load Pin p.u., and the reactive load Q in p.u., drawn from the bus dropped by 10% and 11.5% at grid peak time respectively. In fig. 13. the stability indexes VCPI, and L_{mn} during grid peak hour, show betterment by 0.23, and 0.18 at grid peak timerespectively.

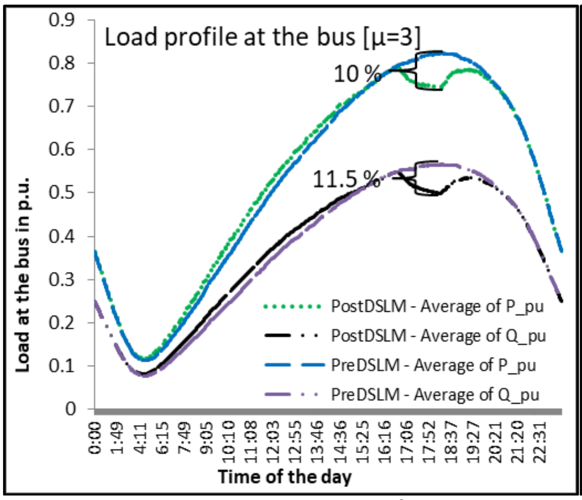

Figure 12. Active/ Reactive Load profile at bus, μ=3

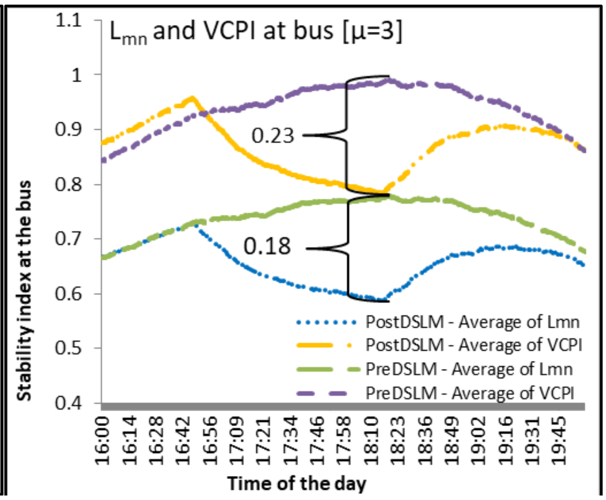

Figure13. VCPI &L_{mn} at bus, during peak hour μ=3

7. Conclusions

Voltage stability is a major concern for power system engineers. In event of any exigency, usually a post event load shedding is exercised as per state transition flow (figure 1). Preventive load shedding scheme is reported [18]. The work presented here effect a finely distributed preventive load shedding scheme for stressed season operations. This affects only fraction of appliances, instead of a blanket tripping of consumer installations or switching areas.This work establishes the fuzzy logic based DSLM for voltage stability as an alternative, to conventional load shedding. We have performed simulations on a representative consumer data, to demonstrate efficacy of the DSLM. This can be visualized as a distributed reactive power consumption process for voltage stability. One of the advantages, of distributed reactive power compensation is to achieve better response time to disturbances [19].This DSLM, injects reactive and active power reserve at point of consumption, finely distributed across the network. The DSLM way to “reactive power compensation” aims to bring down the requirement of reactive power injection by conventional reactive power compensators, thereby reinforcing capability of system to handle voltage instability.

The drop in values of L_{mn}observed at grid peak hour peak, in range from 0.08 to 0.17, for forecast of system state as “Alert” to “In-extremis”. The voltage collapse proximity index “VCPI”drops at grid peak hour, in rangefrom 0.07 to 0.21, for system states “Alert” to “In-extremis”. This drop in magnitude of stability indices indicate improvement in voltage stability of the system, under stress. The drop in reactive power drawn from the bus atgrid peak hour, is seen in range from 4.5% for forecast system state “Alert” to 11.5% for system state “In-extremis”.

This study has been performed on a single cluster of an ilk of consumers, and performance observed are likely to vary with type of consumers and their loading profiles.In a nutshell, benefits of the proposed DSLM, are:

- It preserves precious spinning reserve of reactive power, at generation/ network, which is crucial for the capability of system to cope up with disturbances, and instability. The reactive power reserve is even more precious in case of microgrids, which have limited conventional generation capacity, and inclusion of static VARs in the network, a luxury.
- The consumer comfort has been accorded priority; he defines the deferrable loads, and none of the loads are interrupted, by DSLM. Thisshouldmake DSLM more acceptable by the consumers.

References

[1]Y. Mansour; “Suggested techniques for voltage stability analysis,” Publication 93TH0620-5-PWR, IEEE Working Group on Voltage Stability, 1993.

[2]B. Gao, B. G. K. Morison, and P. Kundur; “Voltage stability evaluation using modal analysis,” IEEE Trans. Power Syst., vol. 7, pp. 1529–1542, Nov. 1992.

[3]Peter Palensky, Dietmar Dietrich; “Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads”, IEEE Transactions on Indl. Informatics, 7, (3), 2011, pp. 381-388.

[4]Prabha Kundur; “Introduction to Power Systems Stability Problem”, in Power System Stability and Control” (McGraw Hill Inc., 1994)pp. 10-11,

[5]A. C. Martins, et al; “Criteria and methodologies established in the ambit of GTAD/SCEL/GCOI voltage collapse task force for studies on voltage stability in the Brazilian north/northeast, south/southeast and north/south interconnected systems,” in Proc. PES Summer Meeting, vol. 1, 2000, pp. 531–536. Y.

[6]Final Report: Voltage Stability Criteria, Undervoltage Load Shedding Strategy, and Reactive Power Reserve Monitoring Methodology (1998). [Online]. Available: http:// www.wecc.biz

[7]Shailendra Baraniya, Manoj Sankhe; “Consumer Co-operation in Demand Side Load Management; an assessment”, Int. Jrnl. of Future Revolution in Computer Sc. & Communication Eng., 3, (8), 2017, pp. 164 – 171

[8]F. Elghitani and E. El-Saadany, "Smoothing Net Load Demand Variations Using Residential Demand Management", IEEE Transactions on Industrial Informatics, vol. 15, no. 1, pp. 390-398, Jan. 2019.doi: 10.1109/TII.2018.2852482

[9]Shailendra Baraniya, Manoj Sankhe; “Demand Side Load Management, and its impact on bus parameters”, presented at 2018 IEEMA Engineer Infinite Conference (eTechNxT), Noida, India, Mar 13-14. 2018.

[10]Siddharth Deshmukh, et al; “Voltage/VAR Control in Distribution Networks via Reactive Power Injection through Distributed Generators”, IEEE Transactions on Smart Grid, 2012, 3, (3), pp. 1226 - 1234

[11]Carson W. Taylor; “What is voltage stability”, in Power System Voltage Stability, (McGraw Hill Inc., 1994, Intl. Edn.,) pp. 27-32.

[12]Shailendra B., etal; “Architecture for smart grid based consumer end solution”, Proc., 13th Int. Conf. of Advanced Communication Technology, (ICACT), Phoenix, Republic of Korea,. 2011, pp: 88-92

[13] Timothy J. Ross; “Properties of membership functions, fuzzification, and defuzzication”, in Fuzzy Logic with Engineering Applications, (John Wiley and sons, 2010, 3rd edn.) pp. 93-94

[14] Timothy J. Ross; “Properties of membership functions, fuzzification, and defuzzication”, in Fuzzy Logic with Engineering Applications, (John Wiley and sons, 2010, 3rd edn.) pp. 98-101.

[15] Dua, D. and Karra Taniskidou, E.; UCI Machine Learning Repository [http://archive.ics.uci.edu/ml]. Irvine, CA: Univ. of California, School of Information and Comp. Sci., 2017.

[16] M. Moghavvemi, F.M. Omar; “Technique for contingency monitoring and voltage collapse prediction”. IEE Proc. Gener. Transm. Distrib. 1998, 145, pp. 634-640.

[17] M. Moghavvemi, O. Faruque;“Real-time contingency evaluation and ranking technique”, IEE Proc. Gener. Transm. Distrib., 1998, 145, pp. 517-24.

[18] S. M. Hashemi, M. Sanaye-Pasand and M. Abedini, "Under-impedance load shedding: a new preventive action against voltage instability", IET Generation, Transmission & Distribution, vol. 13, no. 2, pp. 201-208, Jan. 2019.doi: 10.1049/iet-gtd.2018.5851

[19] Hao Zhu; Hao Jan Liu; “Fast Local Voltage Control Under Limited Reactive Power: Optimality and Stability Analysis”, IEEE Transactions on Power Systems, 2016, 31, (5), pp. 3794 – 3803.