Distributed Voltage Control for Distribution Feeder with Photovoltaic Systems

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***Abstract*—The voltage fluctuations in an active distribution system is a challenging problem which requires an effective solution to empower the expansion of photovoltaics (PV). In this study, distributed voltage control which leverages the smart inverter technology, is proposed as a solution. In distributed voltage control, the reactive power reference for the PV plants are generated using the weighted voltage deviation of selected nodes. The control method is illustrated on a modified IEEE 34 test feeder integrated with two PV plants. The voltage profile of the IEEE 34 feeder with particle swarm optimization based tuned weights and equal weights are compared. Typical results show that the mean squared error for the proposed tuning method is lower with optimized distributed voltage control.**

***Index Terms*—Distribution system, Distributed Voltage Control, Particle Swarm Optimization, Photovoltaics, Voltage Control.**

I. Introduction

In the modern distribution system it is critical to maintain a quality voltage profile, at all times, because of the sensitivity of the customer equipment as well as the economic requirement to minimize losses in the distribution grid. Furthermore, distribution grid codes [1] enforce stringent limits, making it a legal obligation of the Distribution System Operator (DSO). On the other hand, increasing penetration of Distribution Energy Resources (DERs), has completely changed the traditional operation and control landscape of the distribution grid, making voltage control a very challenging control problem for the DSO. The bi-directional power flow needs to be supported by an aging distribution infrastructure originally designed for unidirectional power flow, which further escalates the complexity of the problem.

In a traditional distribution system, voltage control is implemented using regulators and capacitor banks. Since the traditional distribution system consists of unidirectional, top-down power flow with slow changes in loading, this method can be effectively used to regulate voltage in the distribution grid. However, the modern distribution grid is rapidly evolving into a bi-directional power flow distribution system as a result of accelerated integration of distributed PV plants. This phenomenon is changing traditional customers to prosumers; customers who consume as well as produce electric power. The intermittency of solar irradiation causes large variations in the power flow resulting in a degraded voltage profile. Unfortunately, traditional voltage regulators are not fast enough to counter this problem, since they operate using mechanical tap changers. Further, the cost associated with increasing number of tap changes will be significant to the operator due to the degradation of the equipment life time.

Several solutions have been shown to be effective to counter the fast voltage variations associated with PVs in the distribution system [2]. One state of the art solution is to install Distribution Static Var Compensators and dynamic voltage restorers [3]. However, these components are both costly to install and maintain, while needing support infrastructure which might not even be available to the DSO. Another state of the art is to install an Edge of Network Grid Optimizer [4], which provides a more cost effective solution. However, this too still requires additional equipment.

With growing DER penetration, it is evident that the above solutions, where the DSO is solely responsible for voltage control will not be sustainable. The concept of utilizing available end user devices to support distribution grid operations provides a practical and cost effective solution to this problem. This concept has attracted significant traction in the recent years resulting in the Section 4.1.1 of IEEE 1547 getting amended, to allow Distributed Resources (DRs) to actively participate in voltage control [5].

Smart grid technologies will empower the prosumers to get connected to the traditional grid via smart inverters which supports bi-directional power flow. This work is based on the idea that the idling reactive power capacity of the smart inverter is available to be used to support voltage control. The prosumers will be compensated for this ancillary service.

The existing studies in this area are focused on local voltage control using smart inverters [6], where a droop [7] or a volt/watt-var curve based on the local voltage is used as the

This study is supported by the National Science Foundation (NSF) of the United States, under grants IIP #1312260 and #1638321, and the Duke Energy Distinguished Professorship Endowment Fund. Any opinions, findings and conclusions or recommendations expressed in this material are those of author(s) and do not necessarily reflect the views of National Science Foundation and Duke Energy.

978-1-5386-2453-1/18/$31.00 ©2018 IEEE

control method. The assumption is that if each prosumer takes care of the voltage at its own point of common coupling (PCC) [8], then the system voltage will be optimally regulated. Since the system is connected and voltages of all the nodes are interlinked, this logic will be valid. However, if there are nodes that only operate in the consumer mode and do not have any production, then this control method might not provide the optimal voltage profile for the feeder. Therefore, in order to ensure optimal voltage profile across the feeder, it is necessary to take into account the voltage of neighboring nodes. Many solutions are present in literature where optimization is carried out in a completely centralized manner [9]. The pitfall with centralized control for a distribution grid is that the topology is highly dynamic in nature and while consisting of a large amount of nodes. This limits the possibility of implementing a completely centralized control method for voltage control.

This study proposes a distributed voltage control method for voltage control, based on remote voltage measurements apart from the local voltage measurement. The studies conducted thus far on distributed voltage control is limited to multi-agent based message passing techniques that do not use remote voltage measurement [10] or optimization based on estimation of remote node voltages []. The main challenge in the proposed distributed voltage control method is to find the optimum controller weights that controls the reactive power contribution from each node. Reference [11] shows how particle swarm optimization (PSO) can be used in different power system applications. The paper applies PSO as the tool for finding the optimum weights for the implemented distributed control system.

The paper is organized as follows. Section II presents the system used for the study, Section III introduces the proposed voltage control method and Section IV presents the results and compares the performance of the PSO tuned method to the equal weighted method.

II. Distributed Voltage Control

The core contribution of this study is the proposed distributed voltage control method presented in this section. The overview diagram for the proposed method is given in Fig. 1. To implement it in a real system, voltage transducers to monitor the node voltages and a communication channel to transfer the data between the voltage nodes and smart inverters will be required.

The voltage measurements are taken from the four nodes marked with a VT in Fig. 5 and the proposed method is applied on the modified IEEE 34 bus test system. In the modulated control concept the reactive power reference for each inverter is generated using the modulated voltage deviation of the node voltages as shown in Figs. 2 and 3.

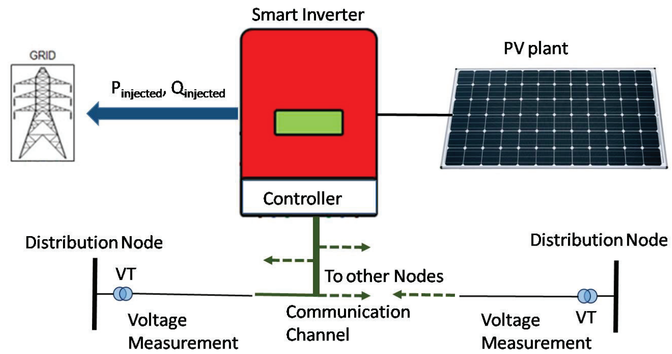

Figure 1. Overview of system architecture for distributed voltage control

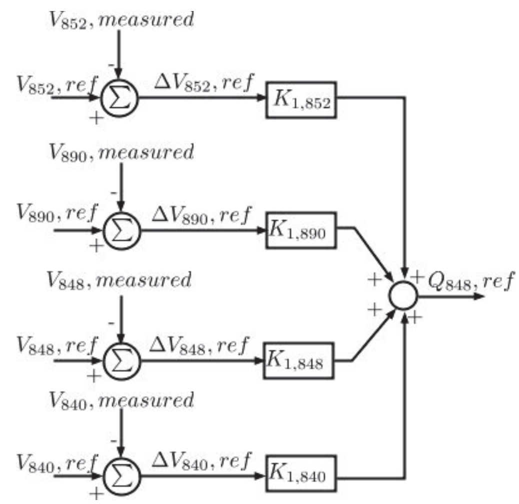

Figure 2. Distributed voltage control method applied to the IEEE 34 test case to generate Var reference for PV at node 848

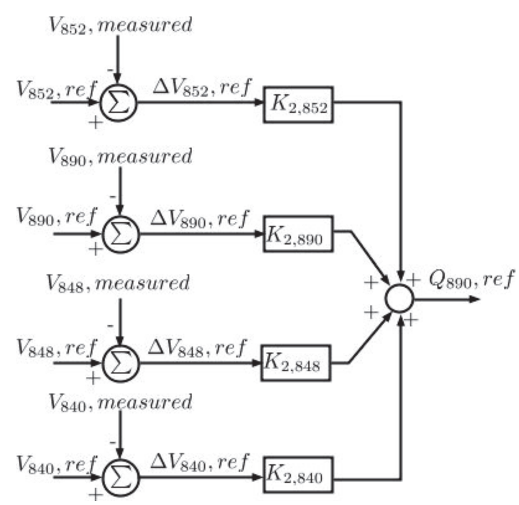

Figure 3. Distributed voltage control method applied to the IEEE 34 test case to generate Var reference for PV at node 890

A. Particle Swarm Optimization

According to [12] swarm intelligence is defined as 'the property of a system where the collective behaviors of the simple agents interacting locally with their environment causes coherent functional global patterns to emerge'. A typical example for swarm intelligence is a school of fish or a flock of birds self organizing in an optimal pattern in space and time. The key feature of the swarm is that the swarm can exhibit very complex collective behavior even though the individuals that constitutes the swarm can only exhibit simple behavior.

Particle swarm optimization (PSO) is a heuristic optimization method learned by studying the behavior of swarms of biological mechanism [13], which was first proposed in [14].

In PSO, the motion of the particles are influenced to move towards both their local best known position (local best) and the global best known position (global best). The updated position of a particle (x_i^{t+1}) after one time step is given by (1).

$$x_i^{t+1} = x_i^t + v_i^{t+1} \tag{1}$$

Here $x_i(t)$ is the current position of the particle i and v_i^{t+1} is the velocity vector that drives the swarm process. This study uses the gbest variant of the velocity vector which is described by (2).

$$v_i^{t+1} = \omega v_i^t + c_1 r_1^t (x_{best,i}^t - x_i^t) + c_2 r_2^t (g_i^t - x_i^t) \tag{2}$$

where, ω is the inertia weight, c_1 and c_2 are cognitive and social acceleration constants, r_1 and r_2 are random numbers between 0 and 1 sampled from a uniform distribution, $x_{best,i}^t$ is the current local best position and g_i^t is the current global best position. The global best is the best position discovered by the swarm at any time step and the local best is the best position a particle has achieved at any time step. The objective function, f, also known as the fitness function is used to quantify the quality of each particle.

1) Evaluation of the Fitness Function: Voltage control can be considered as an optimization problem with the objective of minimizing the mean square error (MSE). In this case, the objective function f is defined as,

$$f = \sum_{i=1}^{k} (V_i - V_{rated})^2 \tag{3}$$

where k is the number of nodes of interest and V_i is the voltage at the i^{th} node. In this study, the MSE is used as the index to evaluate the controller performance.

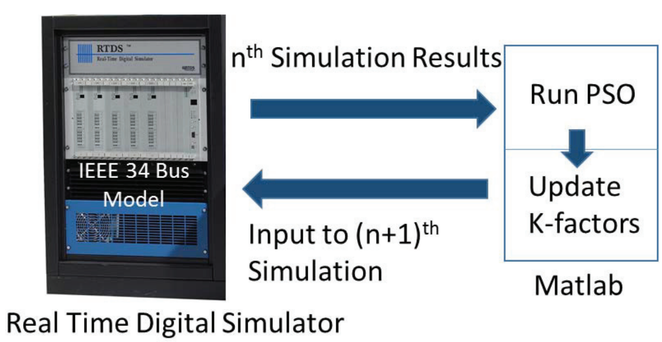

Figure 4. Process flow for optimizing the weight (K) factors

2) Optimizing Weights Using PSO: The algorithm for the PSO implementation given in [11] is used in this paper. Since the optimum weights varies with the level of PV generation, the region of operation is divided into five parts based on solar irradiation, and the optimum set of weights are evaluated using PSO for each part. The modified IEEE 34 bus is simulated on the Real Time Digital Simulator platform and particle swarm optimization is executed in Matlab. The process flow for this exercise is shown in Fig. 4. The process is repeated five times to tune weights in the full range of operation.

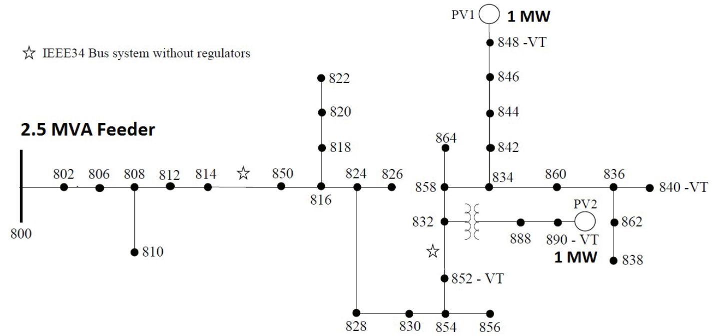

Figure 5. Modified IEEE 34 bus test feeder with two PV plants

III. Simulation Case Study

The test bed used for this study is the IEEE 34 feeder [15] and was a model of a lightly loaded, unbalanced, long radial distribution feeder in Arizona.

Due to the lightly loaded condition of the IEEE 34 feeder, the only limiting operational constraint is the node voltage. Two 1 MVA PV plants are integrated at Bus 890 and Bus 848 and voltage is measured at the nodes 840, 852, 890 and 848, as shown in Fig. 5. Apart from the addition of PV, the IEEE 34 test case is modified by deleting the regulators of the original system.

Due to the resistance a significant change in the sending end voltage can be observed with the variation of active power injection. This phenomenon typically occurs when a cloud momentarily passes over the sun on a sunny day. This will cause voltage flicker in the feeder. However, since the voltage can be also controlled by Q injection, given the spare current injection capability of the smart inverter, the voltage variation can be avoided by increasing the reactive power injection in a controlled manner. By operating the PV plants using a well designed controller, it will be possible to keep the terminal voltage at the specified value or band width. This is the basic principle used for voltage control in this study.

In this case study the, PV plants operate in active power priority mode with no curtailment of active power enforced. Therefore, in a dq reference frame, during normal operation, the controller gives priority to the active currents as given in (4).

$$\begin{aligned} i_{dg} &< I_{dg}^{lim} \\ i_{qg} &< I_{qg}^{lim} = \sqrt{(I_g^{lim})^2 - (i_{dg}^{lim})^2} \end{aligned} \tag{4}$$

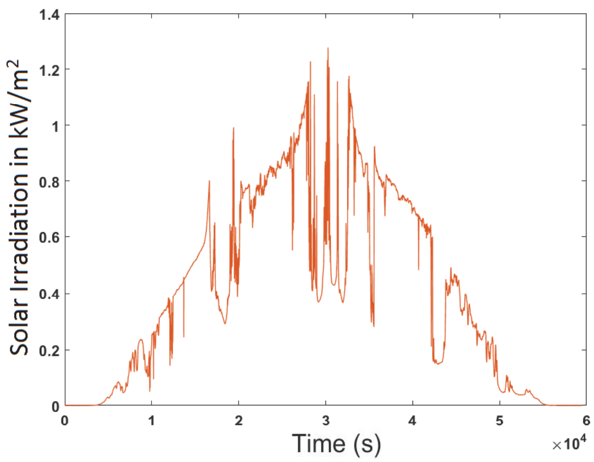

Figure 6. Solar irradiation profile for 2016-07-10 in Clemson

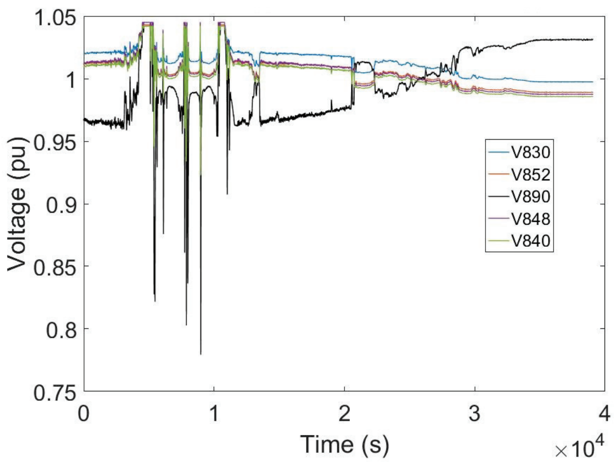

Figure 7. Voltage profile of the feeder for equal weight voltage control

Here I_{dg}^{lim}, I_{qg}^{lim} and I_{g}^{lim} are the limits for d-axis, q-axis and total grid side converter currents, respectively, and i_{dg} and i_{qg} are the d-axis and q-axis current reference to the inner current loop of the PV plant.

IV. Results and Discussion

The simulation is based on the weather data for 2016-07-10 of Clemson, extracted from the Clemson University Real Time Power and Intelligent Systems (RTPIS) Lab weather-station archive. This specific day was chosen because it has significant flicker in the solar irradiation profile as shown in Fig. 6 .

A. Distributed Voltage Control with Equal Weights

A scenario for Var injection using distributed voltage control method with equal weights is simulated first. In order to simulate equal weights, each weight is set to a value of 125. The resulting voltage profile is given in Fig. 7. The average MSE for this profile is 1.708×10^{-3}.

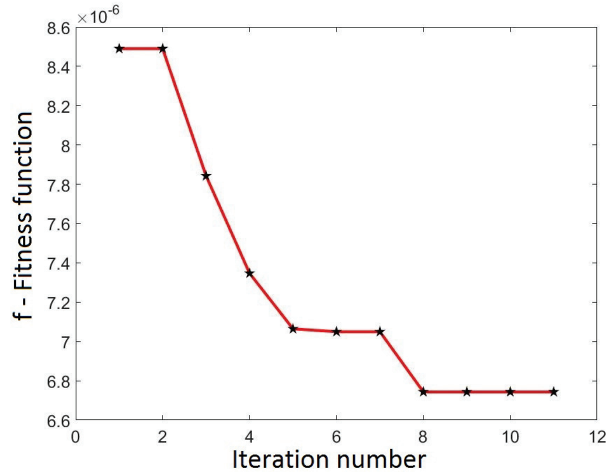

Figure 8. Variation of PSO global best with the number of iterations

TABLE I
Voltage weight factors for the PV plant installed at node 848

Solar Irradiation (kW/m^2)	K_{852}	K_{890}	K_{848}	K_{840}
0	25	15	105	230
0.2	151	74	250	189
0.5	226	34	157	62
0.8	217	0	157	83
1	47	95	64	97

TABLE II
Voltage weight factors for the PV plant installed at node 890

Solar Irradiation (kW/m^2)	K_{852}	K_{890}	K_{848}	K_{840}
0	0	168	26	132.3
0.2	169	24	27	206
0.5	201	191	181	217
0.8	0	97	79	0
1	229	156	154	152

B. Distributed Voltage Control with PSO Optimized Weights

The tuned weights are first found by applying PSO. The variation of the global best with the number of iterations for the 20% irradiation level run is given in Fig. 8, to illustrate the performance of PSO in the heuristic optimization exercise. The resulting weights for the first PV plant is given in Table I and II. The voltage profile for tuned control has an average MSE of 8.45×10^{-4} and is given in Fig. 9. The comparison of the MSE at each time step, compared in Fig. 10 shows that the MSE for the tuned case is lower in a major portion of the simulated time frame.

The results show that tuning the controller using PSO enhances voltage control of the system. The MSE of the tuned method is almost half that of the untuned method. Furthermore, the comparison of the feeder voltages given in Figs. 7 and 9 clearly shows that voltage control is enhanced when the PV plants become involved in voltage control.

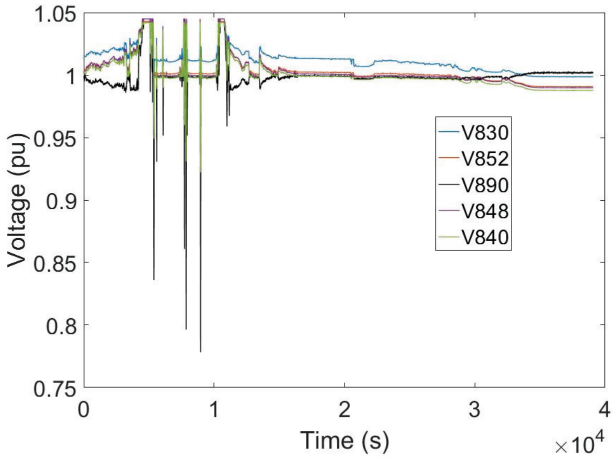

Figure 9. Voltage profile of the feeder for PSO tuned voltage control

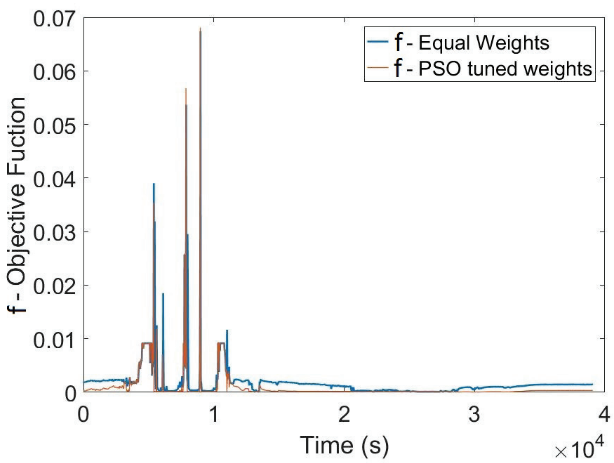

Figure 10. Comparison of MSE for tuned and equal weight cases

V. Conclusion

A new technique for optimal voltage control in a distribution network with photovoltaics has been presented. The highlight of this method is that it is a distributed control technique, making it ideally suited for application to the distribution network. The voltages are measured at the key nodes and reactive power injection for each PV is derived proportionate to some weight of the voltage deviation from the ideal value, of each participant node. The weights are tuned using particle swarm optimization. The results show that this method strengthens the voltage profile of the distribution system. An interesting future work is to investigate the response of this control strategy for different types of distribution test cases in varying operational scenarios.

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Reviewer 1:
Comments: The problem addressed in this paper is of current interest to the industry as more distributed energy resources, and in particular solar PV resources, are added to the distribution grid at the end-use level. The paper presents a practical method for managing and controlling distribution grid voltages.

Reviewer 2:
Comments: -At least one more different distribution system is required to check the performance of the new proposed method of voltage control.
-A comparison for the performance of the proposed method for voltage control application on the two different distribution systems is required.

Authors' Response

Thank you for your feedback. The objective of this paper is to introduce the concept of distributed voltage control and show the viability of using distributed voltage control as a means of voltage control in the distribution system. However, the requested comparison by the reviewer is the scope for future work, which is currently underway.

Reviewer 3:
Comments: paper does not include other work which on this topic, distributed methods proposed, and may even include PSO used in this paper.

Authors' Response

Thank you for your feedback. The newly included references [7], [9] and [10] shows other work done on this topic. The PSO algorithm had to be deleted from the paper due to space constraints (5-page limit) however, the reference [15] included in the paper, describes the PSO algorithm used in this study.

Reviewer 4:
Comments: Introduction is well written on the general idea of the paper. However, initial paragraphs can be reduced in text, and more emphasize can be put on similar research.
How is part A in Section II related to the prior text in this section. Also, can the discussion on the test case be moved to the results section or somewhere similar? Isn't the study generic?
The paper proposes having a communication scheme between VT nodes, to create Q reference for smart inverters at two nodes with PVs. Jumping over PSO (as it is merely an optimization approach), these questions come to mind:
- How feasible is the communication scheme?
- What is the data resolution and its impact on the costs associated to the communication scheme?
- Why have/have not other researches thought of communication-scheme based methods? (maybe lack of literature is seen here more clearly)
- Why are these nodes selected as VT nodes?
- Why aren't we considering all the nodes in the objective function?
- How has RTDS simulation improved the work compared with, say, PSCAD? Are there any actual hardware connections to the RTDS?
- May there be any relation between K factors, say K1-848, and system characteristics?

I hope the authors consider my comments in improvement of their work.

Authors' Response

Thank you for your feedback. The answers to the comments and changes made based on the feedback are given below inline.

How is part A in Section II related to the prior text in this section. Also, can the discussion on the test case be moved to the results section or somewhere similar? Isn't the study generic?
The section II was interchanged with section III and the section III title was changed to 'simulation case study'. The title of part A in Section II (now section III) was deleted since it describes the PV operational mode used in this study. This study validates the concept on a single case study, therefore it is not generic. However, generic implementation is the focus of the future work.

- How feasible is the communication scheme? *With the availability of micropmu technology, this control strategy has become feasible.*

–What is the data resolution and its impact on the costs associated to the communication scheme? *The micropmu which has data resolution up to 120 Hz can be used to implement this control method. However, In this preliminary study the direct internal voltage measurements are used as input to the controller. The cost evaluation and other granular aspects of the control strategy are out scope of this study. However, this will be an interest focus for future work.*
- Why have/have not other researches thought of communication-scheme based methods? (maybe lack of literature is seen here more clearly) *The author has updated the literature review with [9] which uses coordinated control and communication. Many similar schemes have been suggested by different authors. However, the focus is limited to voltage measurements from local terminal. The author believes*

that it is because micropmu technology is still at an incubating stage. Therefore, previous work did not have access to a feasible way of measuring and communicating voltage data in a distribution system to be considered in a control method.

- Why are these nodes selected as VT nodes? *This was based on the sensitivity of the node voltage to a change in active power generation of the controlled generator. The four nodes with the highest sensitivity were chosen as measurement (VT) nodes.*
- Why aren't we considering all the nodes in the objective function? *The voltage of the nodes (apart from the four considered) do not have significant sensitivity to change in voltage based on change of power injection of the PV generators. Therefore, these four nodes can be used to represent the voltages of all the nodes in the system.*
- How has RTDS simulation improved the work compared with, say, PSCAD? Are there any actual hardware connections to the RTDS? *The RTDS provides real time simulation capability, whereas simulation using say, PSCAD will be extremely slow. In this study, there are no hardware connections to the RTDS. The idea here is to extend this work by connecting micropmus in a HIL setup. RSCAD can provide this functionality whereas PSCAD cannot .*
- May there be any relation between K factors, say K1-848, and system characteristics? *Yes there is. K1-848 is the weight of the voltage at node 848 that contributes to reactive power injection of PV1. Therefore, Q injection of PV1 can contribute to controlling voltage at 848.*