DECENTRALIZATION OF POWER FLOW SOLUTION FOR FACILITATING ACTIVE NETWORK MANAGEMENT

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ABSTRACT

The rapid growth in connections of Distributed Energy Resources (DER) is leading to constrains in distribution networks that were not designed with this in mind. The required traditional reinforcement is expensive and so network operators and utilities have sought to use Active Network Management (ANM) as a more effective approach. However, ANM as often proposed relies on a centralized data acquisition and control scheme, which is a challenge if the numbers of DER across the distribution network is very large. In order to avoid these undesirable features, efforts have been directed into decentralizing ANM. This paper presents a decentralized power flow solution that reduces centralized calculations and facilitates ANM. The formulation of the algorithm and the approximations it rests on are described. Simulation results demonstrate that errors in estimating voltages and power flows due to non-local changes in power flow are as small as 0.1%.

INTRODUCTION

Several of the low-carbon generation technologies are distributed in nature and due to environmental, regulatory, and commercial drivers, networks in many countries are seeing a rapid growth in connections of distributed generation (DG) [1]. Furthermore, there are expectations of growth of other distributed energy resources (DER), such as electrical vehicles, energy storage and various controllable loads. Technical and operational issues are arising with the growth in DER connections that were not considered during the network design, which now entail challenges in operation, planning and protection of the distribution system, as discussed in [2] and [3]. To keep network operation safe and reliable, high investment in reinforcement is required to the extent that resources of network operators may not be sufficient to achieve this.

In this context, a more intelligent control and coordination approach using Active Network Management (ANM) has been identified as a means to make more efficient use of the existing network infrastructure, allowing more connections without expensive reinforcement [4]. However, ANM as often proposed relies on a centralized data acquisition and control scheme, which is still highly dependent on data transmission and susceptible to single point failure and it is questionable whether it is practical, at scale, for a distribution network. Moreover, providing information for system-wide oversight and optimisation becomes unrealistic when considering continuously changing outputs from loads and generation in a large network [5]. Besides, the communication infrastructure presently used in many distribution networks is not able to accommodate large amounts of data transfer [9]. For these reasons, algorithms often rely on pseudo-measurements based on historical data and load forecasts, achieving lower accuracy [6]. These undesirable features hinder the energy management in distribution networks.

In order to enable a more realistic implementation for distribution network, efforts have been directed into decentralizing the control and coordination of DER, as discussed in [7] and [8]. The main difficulty for a decentralized implementation is the interdependency between the entire network, where local changes in power output can affect non-local nodes and bring them outside statutory limits. In this context, the aim of this paper is to present a decentralized load flow solution, enabling ANM controllers to calculate expected voltages arising from local and non-local changes in power flow and to take safe decisions for managing DERs. This is to be achieved while avoiding single point failures or a large burden on the communication channel. The mathematical formulation and required approximations for enabling decentralized estimation of voltage sensitivities are described. In order to validate the algorithm, several test case scenarios were simulated in Matlab Simulink, modelling an 11 kV distribution feeder with high penetration of DER, evaluating in this way, the error performance of the proposed decentralized estimator when compared against the centralized power flow solution on DIgSILENT for different power flow changes. The achieved errors are as small as 0.1%, meaning that the approximations undertaken are consistent and acceptable. The outcome of this work can therefore, facilitate the progress of decentralized control and coordination of DER in the distribution network.

The paper outline is as follows. First, a brief problem formulation is given of voltage estimation for a distribution feeder, pointing out different ways for obtaining information from the feeder using centralized and decentralized approaches. Recognising the benefits of a decentralized approach for ANM, the proposed algorithm is introduced, describing the approximations for decentralization of voltage sensitivity and evaluating inherent limitations for utilizing this approach. At the end of this paper, the results obtained in a simulation environment with subsequent conclusions are presented.

PROBLEM FORMULATION

To derive the mathematical formulation for voltage estimation of a distribution feeder, a typical radial circuit with loads (L_i), generation (G_i) and line impedances ($R_i + jX_i$) is considered, as shown in Figure 1.

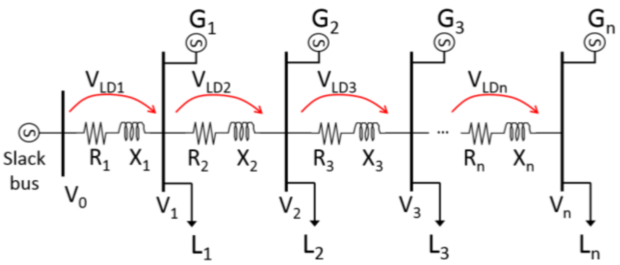

Figure 1. Typical configuration for distribution radial feeder

The voltage at a particular node i can be calculated by subtracting all the line drops from a known nodal voltage, i.e. from the beginning of the feeder (V_0), as shown in equation 1.

$$V_i = V_0 - \sum_{k=1}^{i} V_{LDk} \qquad 1$$

The voltage drop (V_{LDi}) can be calculated as the line impedance multiplied by the current flowing to the node, where the current is the quotient between the complex conjugate of the apparent power and the nodal voltage. Therefore, the voltage line drop is expressed as in equation 2.

$$V_{LDi} = \frac{R_i P_i + X_i Q_i}{V_i} + j\frac{X_i P_i + R_i Q_i}{V_i} \qquad 2$$

For typical conditions of distribution networks, the imaginary part of equation 2 makes little difference to the magnitude of the voltage and can be neglected. Additionally, since the voltage upstream to node i is the sum of all the terms up to the $(i-1)^{th}$ term of equation 1, then the approximate magnitude of nodal voltage can also be expressed as a function of immediate upstream voltage, as presented in equation 3.

$$|V_i| \cong |V_{i-1}| - \frac{R_i P_i + X_i Q_i}{|V_i|} \qquad 3$$

Rewriting equation 3 as a function of upstream voltage and downstream powers, a second order equation is obtained, whose solution is presented in equation 4.

$$|V_i| \cong \frac{|V_{i-1}| \pm \sqrt{|V_{i-1}|^2 - 4(R_i P_i + X_i Q_i)}}{2} \qquad 4$$

It can be concluded from physical conditions that only the positive sign results in significant answer. From equation 4 it is clear that voltage at node i is a function of upstream voltage (which in turn is dependent of all its upstream voltages as well) and power flowing into the node (P_i and Q_i). Hence, it is required high observability of the network for solving the nodal voltage estimation, reason why load flow solution is said to be a centralized problem. Solving this equation in reality is unpractical due to the variable condition of loads and generation of the distribution system as well as the increasing amount of connecting DERs.

In some techniques for decentralizing load flow, two important parameters for proper coordination between controllable devices must be calculated, the rate of change of voltage due to active and reactive power changes, defined in literature [10] as active and reactive voltage sensitivities $\left(\frac{\partial V_i}{\partial P_i} \text{ and } \frac{\partial V_i}{\partial Q_i}\right)$. These parameters enable estimation of local voltage outcome due to possible change in power flow as shown in equation 5.

$$|V_i^{new}| \cong |V_i^{old}| + \frac{\partial V_i}{\partial P_i}\Delta P_i + \frac{\partial V_i}{\partial Q_i}\Delta Q_i \qquad 5$$

The introductory section of [10] reviews some of the techniques for obtaining these sensitivity parameters, either from a centralized or decentralized scheme. Essentially, the centralized approach is computationally demanding and relies on system-wide information but can achieve good results whereas the decentralized approach based on local measurements can calculate only sensitivities to local perturbations.

This paper proposes different approximations for decentralized estimation of voltages sensitivities for any node based on local measurements of voltage and power flow. The approximations take advantage of some peculiarities of distribution feeders and its radial topology.

PROPOSED DECENTRALIZED LOAD FLOW SOLUTION

The first step in designing an algorithm for decentralized ANM is to understand how the centralized problem of load flow is simplified to work with limited observability. Examining the approximations, it becomes clear what local information is required and for what type of network configuration the approximations are valid.

As stated before, by calculating the derivative of V_i in relation to P_i and Q_i, the node sensitivities for each node are obtained and shown in equations 6 and 7.

$$\frac{\partial |V_i|}{\partial P_i} \cong \frac{1}{2}\left[\frac{\partial |V_{i-1}|}{\partial P_i} + \frac{\partial \sqrt{|V_{i-1}|^2 - 4(R_i P_i + X_i Q_i)}}{\partial P_i}\right] \qquad 6$$

$$\frac{\partial |V_i|}{\partial Q_i} \cong \frac{1}{2}\left[\frac{\partial |V_{i-1}|}{\partial Q_i} + \frac{\partial\sqrt{|V_{i-1}|^2 - 4(R_iP_i + X_iQ_i)}}{\partial Q_i}\right] \quad 7$$

To compute these derivatives, it is required the rate of change of upstream voltages due to change in local power flow, which as seen in equations 8 and 9, involves terms supposedly unknown in a decentralized approach.

$$\frac{\partial |V_{i-1}|}{\partial P_i} \cong \frac{\partial |V_0|}{\partial P_i} - \sum_{k=1}^{i-1} \frac{\partial}{\partial P_i}\left(\frac{R_kP_k + X_kQ_k}{|V_k|}\right) \quad 8$$

$$\frac{\partial |V_{i-1}|}{\partial Q_i} \cong \frac{\partial |V_0|}{\partial Q_i} - \sum_{k=1}^{i-1} \frac{\partial}{\partial Q_i}\left(\frac{R_kP_k + X_kQ_k}{|V_k|}\right) \quad 9$$

In a radial feeder, it is safe to make two assumptions. First is that a change in power flow downstream is the same as the power change upstream, i.e. $\frac{\partial P_{i-1}}{\partial P_i} = 1$ and $\frac{\partial Q_{i-1}}{\partial Q_i} = 1$; second is that voltage at the substation is fairly constant with respect to power flow changes $\left(\frac{\partial |V_0|}{\partial P_i} = 0\right)$. It is noteworthy that although interconnected feeders exist in urban areas, the open points ensure a single active path, leaving other paths available for reconfiguration after an outage or constraint condition [11]. Therefore, it is justifiable to assume a radial feeder for the proposed methodology. Applying the approximations to equations 8 and 9, result in equations 10 and 11.

$$\frac{\partial |V_{i-1}|}{\partial P_i} \cong -\sum_{k=1}^{i-1}\left(\frac{R_k}{|V_k|}\right) \quad 10$$

$$\frac{\partial |V_{i-1}|}{\partial Q_i} \cong -\sum_{k=1}^{i-1}\left(\frac{X_k}{|V_k|}\right) \quad 11$$

Substituting these results in equations 6 and 7 it is obtained equations 12 and 13 respectively, appropriately placed at the bottom of the page. According to these equations, aside from local parameters (V_i, P_i and Q_i) , it is essential for each device to also know the sum, up to its upstream node, of the quotient between line impedance and nodal voltage $\left(\sum_{k=1}^{i-1}\frac{R_k}{|V_k|}, \sum_{k=1}^{i-1}\frac{X_k}{|V_k|}\right)$. The impedances can be considered constants for each network configuration without considerable loss of precision, therefore, can either be measured in a centralized fashion or pre-programed in the controllable devices. However, values of nodal voltages and power flows oscillates, and are expected to be locally measured in a decentralized approach. A possible way to further decentralize this algorithm is to consider approximate ratios of impedances and nodal voltages by approximating non-local voltages by an expected value. In order to validate this approximation, error performance will be examined.

To evaluate how nodal voltages affect estimation of the summation term, a feeder with 10 nodes with resistance and reactance of 0.25 Ω node-to-node and nominal line voltage of 11 kV is used as test case. By varying the voltage in all feeders from 0.97 to 1.03 p.u, which is the safe operating limit in UK and calculating the sum up to each node, it is possible to evaluate the errors in assuming a fixed mean voltage. The plot in Figure 2 presents the values for the active power change for all nodes with varying voltage, highlighting the extreme cases.

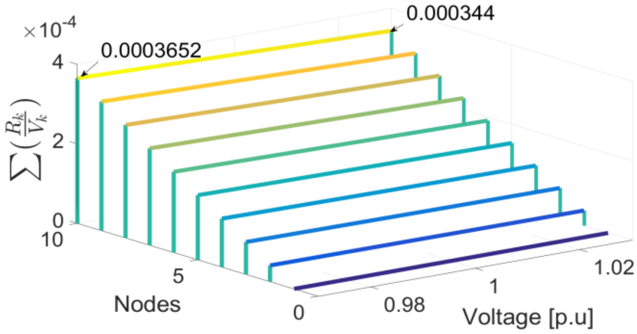

Figure 2. Absolute values for the summation term from equation 10 plotted against all nodes for varying voltages.

It is noticed that if the voltage is considered constant at 1 p.u for calculating the summation term, the maximum error will be around 3% when voltage is actually 1.03 p.u or 0.97 p.u. This result shows it is feasible to consider constant non-local voltages for calculating sensitivities.

$$\frac{\partial V_i}{\partial P_i} \cong -\frac{1}{2}\sum_{k=1}^{i-1}\left(\frac{R_k}{|V_k|}\right) + \frac{1}{2}\frac{\left(|V_i| + \frac{R_iP_i + X_iQ_i}{|V_i|}\right)\left[\sum_{k=1}^{i-1}\left(\frac{R_k}{|V_k|}\right)\right] - 2R_i}{\sqrt{\left(|V_i| + \frac{R_iP_i + X_iQ_i}{|V_i|}\right)^2 - 4(R_iP_i + X_iQ_i)}} \quad 12$$

$$\frac{\partial V_i}{\partial Q_i} \cong -\frac{1}{2}\sum_{k=1}^{i-1}\left(\frac{X_k}{|V_k|}\right) + \frac{1}{2}\frac{\left(|V_i| + \frac{R_iP_i + X_iQ_i}{|V_i|}\right)\left[\sum_{k=1}^{i-1}\left(\frac{X_k}{|V_k|}\right)\right] - 2X_i}{\sqrt{\left(|V_i| + \frac{R_iP_i + X_iQ_i}{|V_i|}\right)^2 - 4(R_iP_i + X_iQ_i)}} \quad 13$$

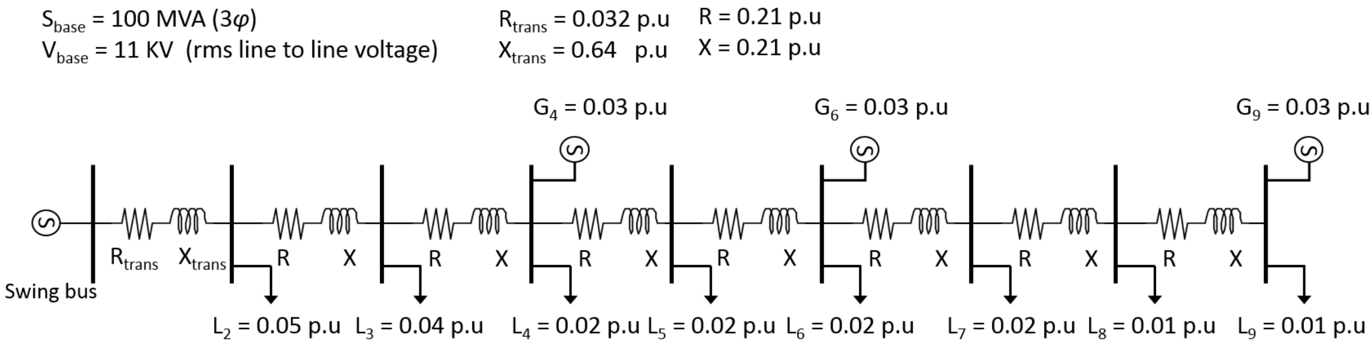

Figure 3. Single line diagram of a radial feeder for evaluating decentralized estimation errors

RESULTS

In order to evaluate the estimation error, a test case is proposed, represented in the single-phase diagram of Figure 3, conveniently positioned at the top of this page. The test case considers typical conditions of distribution system, with base line to line voltage of 11 kV, three phase base apparent power of 100 MVA, line impedances of $0.21 + j0.21\,p.u$ node-to-node and substation transformer impedance of $0.032 + j0.64\,p.u.$ In the represented feeder, there are three controllable distributed generation at nodes 4, 6 and 9, all integrated into a possible ANM scheme. As discussed, the purpose of this work is to enable decentralized voltage estimation based on approximate sensitivities for the controllable devices to take safe actions in managing DERs without breaching statutory limits.

As an example, suppose that the controllable device located at node 9 is requested to increase its power output in 1 MW. All devices composing the ANM structure can estimate their local voltage outcome for this action even though it is a non-local action and ensure safe operation. Note that estimation is still local, i.e. the devices cannot estimate what are the voltage outcome of other nodes, rather they can only estimate local impacts that non-local actions will cause. Figure 4 compares voltage estimation using a centralized load flow solution from DIgSILENT and the proposed local estimation. The respective errors are shown in Table I. The maximum error occurred at the fourth node, with error around 0.05%.

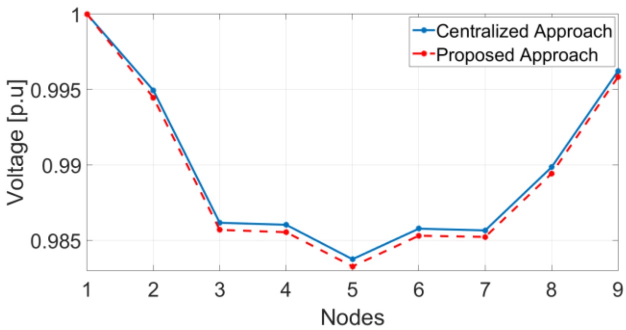

Figure 4. Result from estimation using proposed approach, for test case of Figure 3 with an increase of 1 MW of generator 9.

Table I. Voltage errors obtained from proposed estimator

Nodes	2	3	4	5	6	7	8	9
Error [10^{-2} %]	4.94	4.78	5.	4.8	4.78	4.33	4.3	4.

For evaluating the decentralized power flow estimation based on the premise of $\frac{\partial P_{i-1}}{\partial P_i} = 1$ and $\frac{\partial Q_{i-1}}{\partial Q_i} = 1$, Table II shows the errors obtained with the change of 1MW at node 9 and its impact on all other nodes. Note that the errors are negligible for radial topology, reaching maximum error of 0.577×10^{-5} % at node 7.

Table II. Power flow errors obtained from proposed estimator.

Nodes	2	3	4	5	6	7	8	9
Error [10^{-6} %]	4.1	3.3	2.4	5.4	4.6	5.77	3.6	0.2

The approximations that directly affect the estimation are the voltage sensitivities, which consider a fixed voltage of 1 p.u. In cases where this is considerably false, higher errors are expected. This is observed in Figure 5, which presents the decentralized estimation compared with centralized approach for the same scenario but with a curtailment of 1 MW in generator 6. This resulted in bad sensitivity approximations, with highest error of 0.135% at node 8.

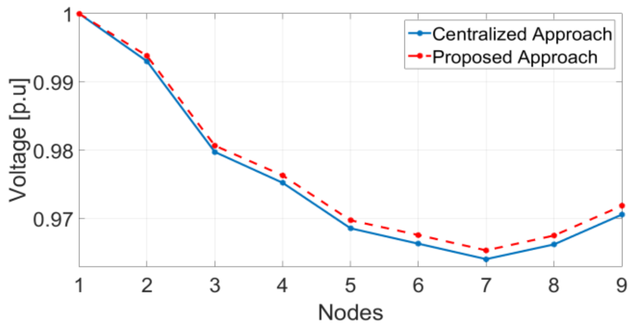

Figure 5. Result from estimation using proposed approach for test case of Figure 3 with a curtailment of 1 MW of generator 6.

Another interesting analysis for validating this approach is to evaluate how error of impedance measurement can affect the proposed estimation. A typical way to determine line impedances for state estimation is to use the length of cable and resistivity provided by vendor. This may not be accurate and therefore it is relevant to consider how the proposed algorithm performs with errors in assumed line impedance. Figure 6 presents the error performance when the proposed algorithm is executed for the same test case scenario of Figure 4 but with error of 10% applied in impedance measurement.

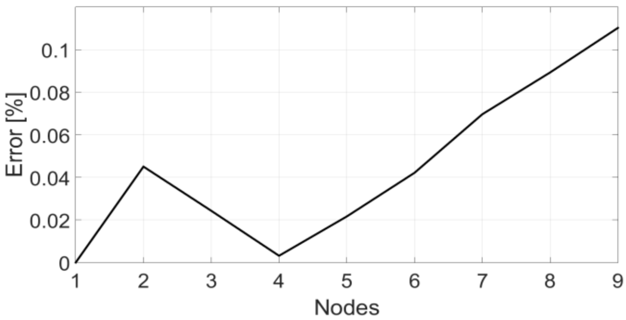

Figure 6. Error performance when considering impedance measurement with 10% error.

Errors are still tolerable for ANM, reaching maximum of 0.11% at the end of feeder. It is noteworthy that this instrument error also influences centralized approaches, not being a specific drawback of this approach.

CONCLUSION

This paper sets out a decentralized estimation algorithm that is capable of providing good estimates of node voltages given power injections from distributed devices. It was designed to facilitate development of decentralised ANM, reducing the reliance on centralized sensitivity calculations. The description has discussed the approximations in the context of a radial network topology and the need to estimate changes in node voltage due to non-local actions. The proposed method has the advantage of relying only on local information to calculate approximate sensitivities, increasing the network observability without requiring too much data transfer between devices. The main objectives were to avoid a large burden on the communication infrastructure and avoid single point failure (typical difficulties in traditional centralized architectures) and to show this can be achieved while maintaining good accuracy in comparison to a centralized approach.

Some drawbacks were observed. For instance, for extreme cases where voltage is far from nominal, the voltage sensitivity is inaccurate. Nevertheless, the ANM is supposed to be operating inside voltage constraints, forcing back to this condition by managing DERs. Another limitation of the proposed method is that its approximations apply to radial topologies only. Consequently, the controllable devices from the ANM must have means to detect network reconfiguration when switches are operated.

Acknowledgments

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