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A method of low voltage residential micro-grids management using AMI/GIS systems and its application benefits

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Most of the countries in the world have a futuristic vision of generating at least 33% of total installed generation capacity from the renewable sources like wind, solar etc. by 2020. As part of the vision, one of the key steps that are being taken is to integrate residential micro grids in large scale at low voltage distribution level. In this paper, we propose a novel and unique algorithm to effectively monitor and control the residential micro grids (MG) connected to low voltage radial distribution systems. An Advanced Metering Infrastructure (AMI) & Geographical Information System (GIS) based near real-time load flow method is developed for this purpose. Proposed method along with weighted graph representation of each 1-phase network connected to a 3-phase distribution transformer (DT) helps in real-time monitoring & control of residential micro grids at individual DT level. A case study is performed on standard IEEE 33 bus radial system demonstrating the working method of proposed algorithm and its major applications for distribution system automation & control are discussed.

Introduction

Distributed generation includes wide range of prime mover technologies such as gas turbines, combustion engines, wind-power, photo voltaic, fuel cells and micro turbines which generate power in a decentralized manner and connect to grid at distribution voltage level. Most of the emerging distributed generation technologies require smart inverter to interface with distribution grids. These technologies produce lower emissions and have the potential to negate overall cost investment by deferring additional transmission & distribution assets and adding more centralized generation facilities [1].

In order to give a more systematic view towards distributed generation and its resources, a subsystem called ''micro grid'' is introduced which manages and controls distributed generation and associated loads in a local manner. Thereby it reduces the need for dispatching the generation & load centrally [2]. These micro grids owned by private or public–private entities, generate power to supply local loads and export additional power available to utility grid or import required power from utility grid based on local load demand and utility grid conditions [3]. Intentional & un-intentional islanding schemes were defined to operate these micro grids in a safe manner during fault conditions on utility grid.

With the evolution of micro grids & its integration with utility grid across various countries, one key strategy that distribution utilities are aggressively driving is to encourage residential micro grids wherein end consumer generates power in his/her home or building premises and supplies or draws power to low voltage distribution systems through net metering concept [4]. Associated switch based mechanism helps in auto-disconnecting residential micro grids from low voltage grid during faults or disturbances. In this paper, we define any distributed generation that happens behind the net meter as residential micro grid. Smart homes or buildings with residential micro grids as shown in Figure 1, are going to be key next step in smart distribution arena which could contain different energy sources with predominantly solar PV roof tops being the major ones, associated storage devices and a controllable

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load. Addition and application of these distributed energy sources on low voltage grids can cause as many problems as it can solve [5].

Many solutions were proposed in literature to intelligently manage and control micro grids, which usually connect to grid at distribution voltage levels of 33 or 11 kV, as independent subsystems or as a distributed energy resources [6–9]. On the residential micro grids side, which usually connects to grid at distribution voltage levels of 400 or 230 V, most of the research is conducted in developing optimal demand response system which can effectively manage local generation, load and storage systems to achieve demand side management within smart home or building premises. Recent trends also include developing DC micro grids, which directly supply DC power to loads [10–12].

In this paper, we propose a novel and unique technique to effectively monitor and control the residential micro grids connected to low voltage radial distribution systems. An AMI & GIS based near real-time load flow algorithm is developed along with graph theoretical representation of each single phase network connected to distribution transformer. This algorithm using AMI communication network & GIS features helps in monitoring total & concentration of residential micro grid generation per phase of distribution transformer at any instant of time. A case study is performed on standard IEEE 33 bus system demonstrating the working method of algorithm and its major applications are analysed.

Further, this paper is organized as section ''AMI & GIS technology — recap'' introduces AMI & GIS systems, Section ''Proposed methodology'' contains proposed algorithm for AMI/GIS based load flow with residential micro grids, Section ''Case study'' depicts case study on a standard IEEE test system and Section ''Algorithm benefits'' discusses applications of proposed algorithm followed by key contribution & conclusion in Sections ''Algorithm benefits'' & ''Key contributions and constraints''.

AMI & GIS technology — recap

Power distribution typically starts after sub-transmission voltage level of 33 kV and consists of several 11 kV feeders supplying power directly to industrial loads. Commercial and residential loads will be supplied power after stepping voltage down to 400/230 V using several distribution transformers (DT). Government entities in several countries are encouraging and providing large scale subsidies to end consumers to install residential micro grids at their premises [13]. These end consumers, typically commercial and residential loads constitute significant amount of overall load on distribution system and large scale penetration of residential micro grids under each distribution transformer in near future poses tremendous challenges to distribution utilities in operating and managing the distribution grid. Hence there is a need to develop technologies which can effectively monitor and control the residential micro grid generation in each phase of distribution transformers connected to all 11 kV feeders in distribution systems.

At the same time distribution utilities are eyeing on recent developments and installations in smart distribution like Advanced Metering Infrastructure (AMI) and Geographical Information System (GIS) to manage these challenges [14]. AMI system components measure various electrical parameters at regular intervals of time through smart & net meters, and transfer measurement data continuously through 2-way remote communications as depicted in Figure 2. They provide mechanisms to collect & transmit detailed time based measurement data to various utility hosts or third party servers. AMI typically refers to or includes smart meters at customer premises with remote disconnect & load control capability using load control relays, communication network between the consumer (smart/net meter) and utility service provider to transfer data, Outage Management System (OMS) to handle outages, Network Management Systems (NMS) to monitor & maintain network topology, and Meter Data Management System (MDMS) for data reception and analytics [15]. On the other hand, Geographical Information System (GIS) manages hardware, software, data capturing & integration, analysing & displaying all forms of geographically referenced information. GIS represents each asset of distribution system with a unique symbol, ID, tag and embed various decision logic's to connect these assets in a logical fashion. Within GIS system, it is possible to link customer information & measurement data from AMI's MDMS or NMS system with geographically represented assets allowing utilities to proactively monitor the distribution grid [16].

Proposed methodology

In this section AMI/GIS based load flow method for monitoring residential micro grids along with graph theoretical representation of single phase network is presented. Following are the proposed algorithm steps,

Step 1: Consider a single-phase network with residential micro-grids connected through net meters and normal loads connected through smart meters on AMI network.

Step 2: Represent the network in suitable GIS software indicating the location of distribution transformer(s), electric poles, smart meters, and net meters connected through distribution power lines. Each of these electrical assets is represented with a unique asset ID tag in GIS database [17].

Step 3: Identify the supply phase (A, B or C) to which single phase meters are connected using suitable phase identification algorithms [18], if required.

Step 4: Represent Meter ID of each smart & net meter as a function of asset ID tags of distribution transformer, supply phase, branch lateral & sub-lateral (if exists) and electric pole to which it is connected to, indicating the connectivity of meter from electric pole to upstream distribution transformer.

Step 5: Assign these Meter ID's in ascending or descending order such that meter positions at each electric pole, represent total load at that point in a logical manner (like load bus) and depict distribution line connectivity in a radial manner (as a series of load buses) until the end of each branch sub-lateral, lateral or line of that particular phase.

Step 6: Perform time synchronization of all meters in AMI network including 3-phase distribution transformer meters at regular intervals of time before computing the load flow.

Step 7: Read snapshot data of all meters connected to a particular phase at regular intervals of time containing voltage, current, net real and reactive power measurements.

Step 8: At each pole location represented as load bus, compute the bus voltage, net real powers and currents from individual meter measurements connected to that bus using Eqs. (1)–(5).

$$Voltageatanybus, V_i = \left[\frac{V_1 + V_2 + \ldots\ldots.. + V_n}{n}\right] \quad (1)$$

$$Poweratanybus, P_i = [\pm P_1 \pm P_2 \pm \ldots\ldots \pm P_n] \quad (2)$$

$$Loadcurrentatanybus, I_i = [\pm I_1 \pm I_2 \pm \ldots\ldots.. \pm I_n] \quad (3)$$

$$ResidentialMGgenerationinkWatanybus, P_i = [P_1 + P_2 + \ldots\ldots\ldots + P_m] \quad (4)$$

$$ResidentialMGgenerationcurrentatanybus, I_i = [I_1 + I_2 + \ldots\ldots.. + I_m] \quad (5)$$

where 'i' represents load bus or electric pole, 'n' represents total no. of meters connected to that bus with '+' sign indicating import of power & '−' sign indicating export of power by meter and 'm' represents no. of net meters exporting power to grid at that bus during any instant of time.

Step 9: Identify the intersection points which represent the locations where sub-laterals are connected to branch laterals and branch laterals are connected to distribution phase lines. Number each of the intersection point from end to the beginning of each phase line in a sequential order.

Step 10*:* Staring from the end load bus of each branch sub-lateral or lateral identified by intersection points in step 9, compute the power or current flows sequentially between subsequent buses using Kirchhoff's current law, first in sub-laterals and then in branch laterals using Eq. (6) (refer to appendix). Finally compute power flows in distribution phase lines based on calculated power flows in branch laterals and at load buses (refer step 8) directly connected to the phase line,

Power or current flow between any two buses 'i' & 'j' is equal to, $I_{ij} = (I_{in,i} - I_i)$ or $(I_{in,j} + I_j)$ (6),where, $I_{in,i} = Netincomingcurrentatbusi$
$I_{in,j} = Netoutgoingcurrentatbusj$
$I_i, I_j = Netloadcurrentsatbusesi\&j$

Step 11: Represent each phase line of 3-phase distribution transformer as a weighted directed graph, with number of vertices or nodes representing the phase supply point, 'end of line' points for branch laterals & phase lines and selected intermediate load buses. Edges represent the line sections connecting these vertex points.

Step 12: Compute and represent the cumulative residential micro-grid generation & load in each edge (line section), net power outflow at each vertex and assign edge weights in the order of increased residential MG generation in line sections represented as edges.

Case study

Case study on standard IEEE 33 bus test system as shown in Figure 3 is considered for demonstration purpose. Entire IEEE 33 bus radial distribution system structure is being considered as any of the single phase network connected to 3-phase distribution transformer of larger network shown in appendix (Figure 11). Proposed load flow logic is computed using VB based programming tool — Quick Test Professional. Residential MG & meters data is simulated randomly in lab between 0–15 kW with actual meters data captured from Canadian buildings as reference [19]. Load flow currents in each line section of 33 bus system are computed. Entire 33 bus system is represented as a weighted directed graph [20] as shown in Figure 4. Each of the graph's vertex (node) and edge for the test system are considered as per steps 11 & 12 of algorithm in Section "Proposed methodology". Net load flow currents in each edge & incoming/outgoing currents at each node are further captured in Table 1.

Weighted directed graph with vertices representing points A–L of test system in Figure 3 is shown in Figure 4, Weights 1–5 (can be any integer 'n' in general) shown in directed graph & Table 1 represents the concentration of residential MG generation in amperes at any instant of time in each edge of the graph, which in turn represent line sections of corresponding test system.

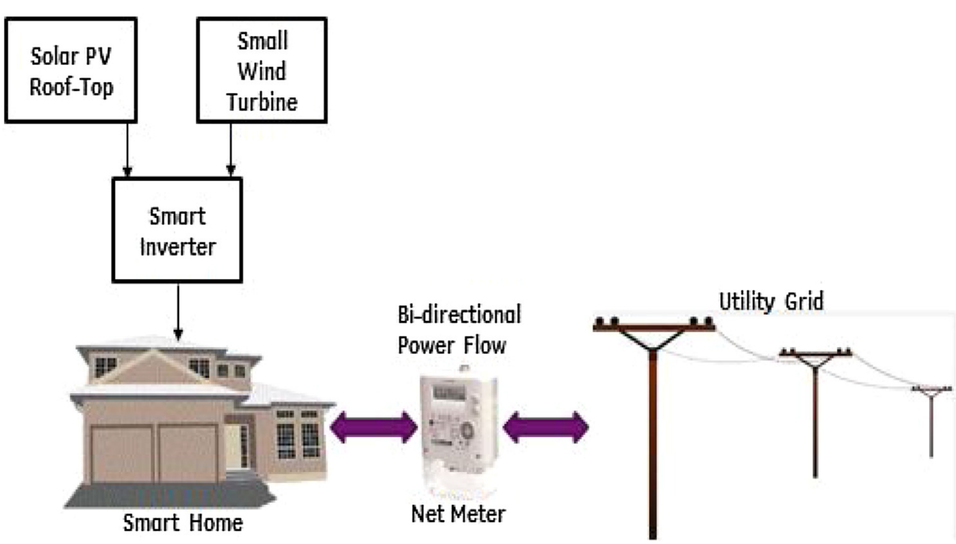

FIGURE 1
Residential micro grid concept.

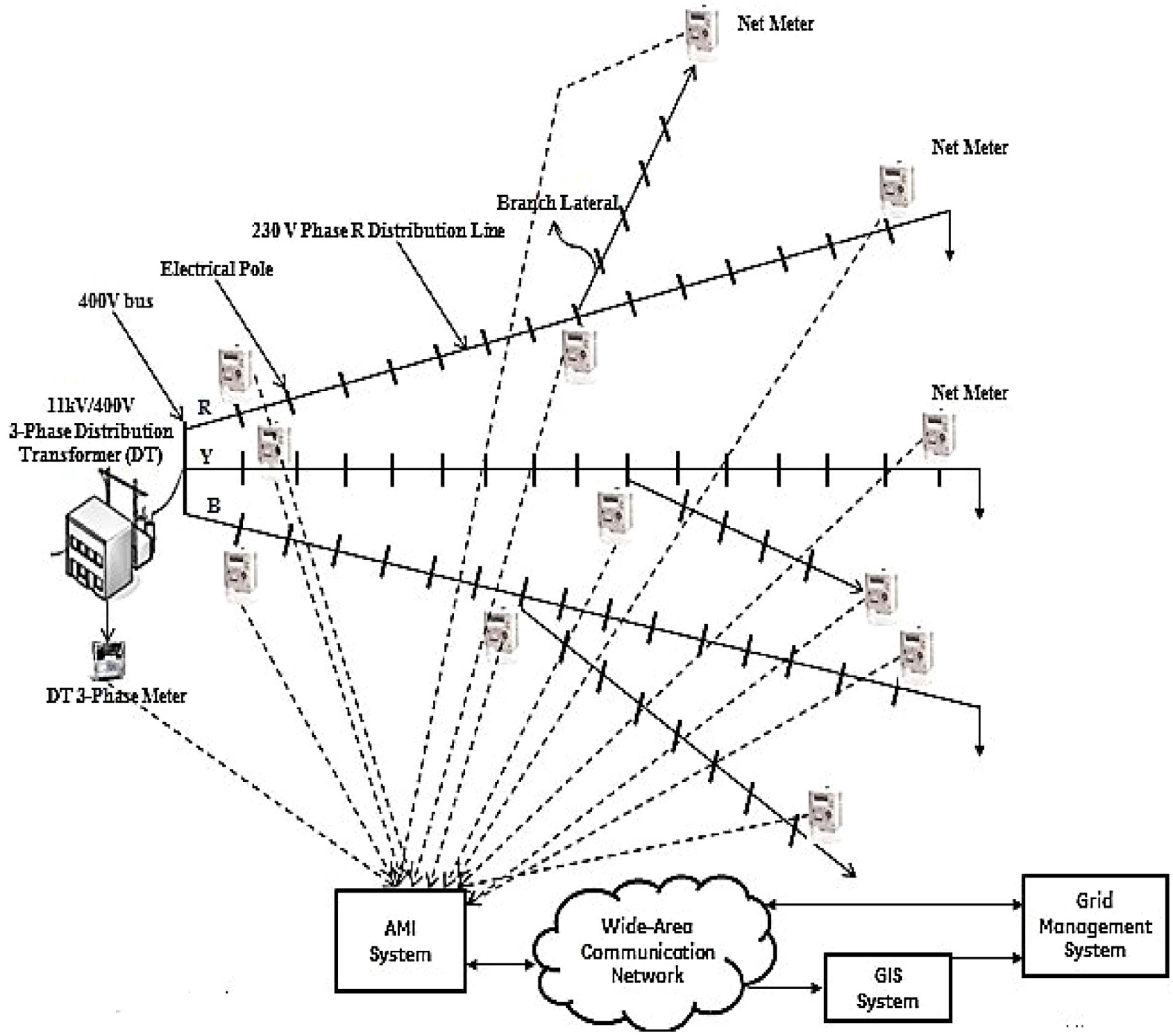

FIGURE 2

Typical distribution system with sample net meters.

Higher the weight (for example edges B → C and J → K) shown in the graph for a particular edge, higher is the amount of residential micro grid generation in that line section represented by that edge. By computing the load flow in near real-time at regular intervals of time, it helps distribution utilities in monitoring amount of residential micro-grid generation in each phase and its concentration spread across different line sections of phase. Applications of the proposed methodology are discussed further in next section. An experimental setup with smart and net meters has been made in lab for simulation as shown in Figure 5.

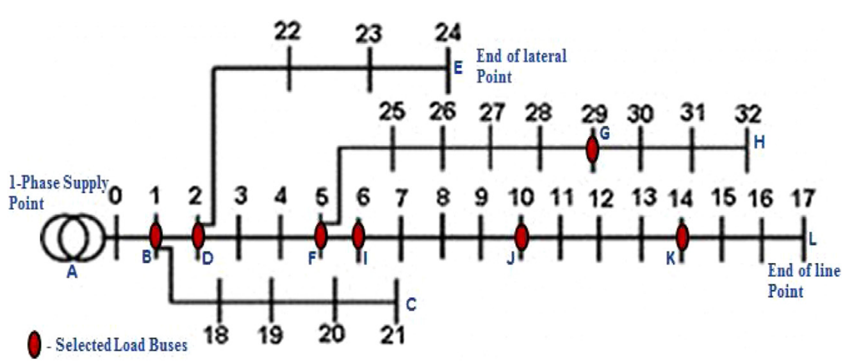

FIGURE 3

IEEE 33 bus radial distribution system.

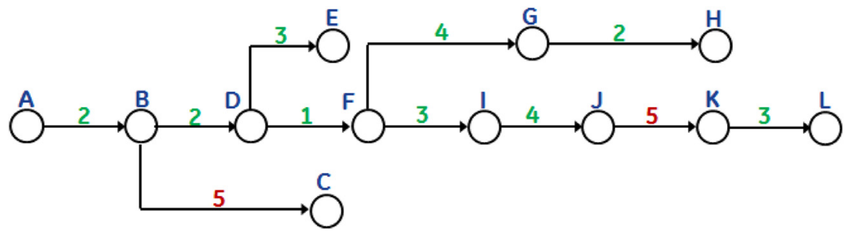

FIGURE 4
Graph computation results for 33 bus system.

TABLE 1
Simulation results.

Edge	Load buses	Residential MG generation O/P current in A	Load current in A (power demand)	Edge weight
A → B	0	20 (4.6 kW)	30 (6.9 kW)	2
B → C	18–21	35 (8.05 kW)	85 (19.6 kW)	5
B → D	1–2	20 (4.6 kW)	50 (11.5 kW)	2
D → E	22–24	25 (5.75 kW)	80 (18.4 kW)	3
D → F	3–4	15 (3.45 kW)	70 (16.1 kW)	1
F → G	25–29	30 (6.9 kW)	165 (37.9 kW)	4
G → H	30–32	20 (4.6 kW)	60 (13.8 kW)	2
F → I	5–6	25 (5.75 kW)	40 (9.2 kW)	3
I → J	7–9	30 (6.9 kW)	80 (18.4 kW)	4
J → K	10–14	35 (8.05 kW)	120 (27.6 kW)	5
K → L	15–17	25 (5.75 kW)	100 (23 kW)	3

Algorithm benefits

In the above section monitoring the concentration of residential micro grid generation in single phase network of 3-phase distribution system with the help of weighted direct graph methodology is represented. Proposed load flow method apart from monitoring residential micro grid generation, can be further used for distribution automation applications. Net meters acting as interface in connecting micro grids to utility grid play a key role in controlling micro grids, based on commands sent from utility controller using AMI network communication. In order to demonstrate these applications as a case study, 3-phase distribution system is considered to consist of three single phase networks of type IEEE 33 bus system as shown in Figure 3 for R, Y and B phases. Following are the applications (not limited to) of proposed method,

FIGURE 5
Lab experimental setup with smart/net meters.

A. Voltage monitoring & control

3-phase distribution system supplies power to 3-phase and 1-phase customers at voltage levels of 400 V and 230 V respectively. Voltage limits should be maintained at ±5% of rated voltage in the entire distribution line due to operational constraints [21]. With a rated voltage of 230 V at single phase level, voltage range limits apply as 218.5 V to 241.5 V. Due to dynamic load variation conditions on each phase of the 3-phase distribution system, single phase voltage values tend to violate the operational limits specifically at end of line points. With the integration of residential micro grids at low voltage level, it can make the situation even worse. Hence monitoring of voltage at each load bus (electric pole) is very critical in operation of distribution systems with integrated residential micro grids as shown in Figure 6 for example below.

For example, consider that 3-phase distribution system is operating at a specific load condition of 145, 160 and 200 kW on R, Y and B phases respectively. Proposed load flow algorithm is used to compute the voltage values at load buses 1 to 17 using simulated net meters load data, computed bus & line currents along with line impedance values considered from standard distribution loading guide [22]. It can be observed that voltage at load bus 17 of phase B is 213.1 V, which is not in the operational limits. Voltage regulator or tap changer with single phase voltage control capability can be used for bringing the voltage values within limits.

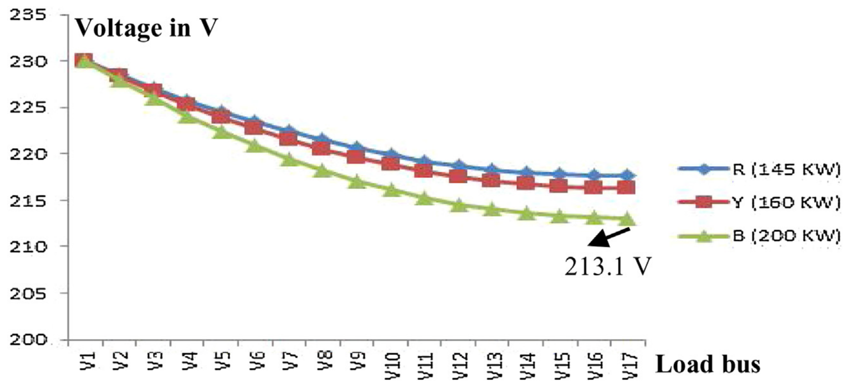

FIGURE 6

Computed voltage values with load flow algorithm.

B. Phase balancing

3-Phase distribution systems operate with 80% of single phase consumers distributed across 3 phases of the distribution system. Presence of these single phase loads on each phase causes loading on each phase to become uneven, resulting in phase unbalance condition [23]. Due to this phase unbalance situation, technical losses increases in the distribution system and unbalance current flows in the neutral of the system. It is also proven in literature that 3-phase distribution transformers failed in large percentage, due to a particular phase winding/insulation damage caused by prolonged overload on that phase [24]. Hence it is important for utilities to maintain phase unbalance index within the specified limits. However with the integration of residential micro grids at low voltage level, phase unbalance index can increase to a worst level if not properly monitored and controlled continuously. Proposed method of monitoring residential micro grid generation helps in mitigating the phase unbalance condition.

Consider a situation where present loading on each phase of 3-phase distribution system is 240 kW, 270 kW and 225 kW in R, Y & B phases respectively, measured at the supply end of distribution transformer. Phase unbalance index (PUI) can be computed as,

$I_{in,j} + I_j$

where, average power is the average of all three phase powers. PUI for present load condition can be computed in this case as 17.24%. From Figure 4 (weighted graph) and Table 1 we know the total & concentration of residential micro grid generation available in each single phase network. Net meters do possess remote disconnect switch which can be controlled to connect/disconnect the individual residential micro grid from the utility grid. If the available residential micro grid generation from R & Y phases is controlled to supply 15 kW (from edges B → C & J → K) & 45 kW (from edges B → C & D → F to K → L) respectively with the help of net meters control capability, then load on all the phases become 225 kW at supply point (DT) making PUI to be ~ zero. In practical scenarios, though it may not be possible to make PUI to exactly zero always, but definitely a reduced PUI index can be achieved. Using effective control mechanism of residential micro grid generation through net meters phase unbalance can be mitigated in all 3-phases of distribution systems, reducing technical losses and increasing the life expectancy of distribution transformers (DT).

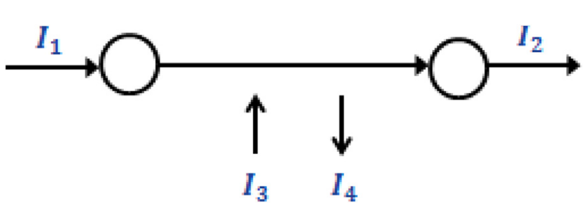

FIGURE 7

Monitoring each edge of weighted graph.

C. Load balancing

Load unbalance is defined as the difference or gap between amount of supply power available and load demand at any instant of time. Availability of residential micro grid generation at any instant of time may or may not benefit the utility based on the load unbalance factor. Based on the government regulations laid out in operating residential micro grids connected to utility grid, certain distribution utilities want to control net residential micro grid generation to supply fully, partially or not to utility grid [25]. Measured load demand on each phase of the distribution transformer and available power supply at any instant of time directs the residential micro grids operation. Proposed methodology of monitoring total & concentration of residential micro grid generation available in each single phase network helps in achieving load balance very accurately. Distribution utilities driven by revenue profits may cut down the additional residential micro grid generation output to utility grid in case of excess availability whereas utilities driven by reduction of carbon emissions may continue to use micro grid generation to the full extent available. For example, consider a distribution system operation scenario where supply power, load demand and net residential micro grid generation available are as shown below,

Case	Supply (kW)	Demand (kW)	Res. MG generation (kW)
Case 1	150	130	50
Case 2	150	200	50
Case 3	150	150	50

Distribution utilities of type ‘A’ driven by profits, will use 20 kW of residential micro grid generation in case 1, 50 kW in case of case 2 and ‘0’ kW in case of case 3. On the other hand distribution utilities of type ‘B’ who are driven by reduced carbon emissions or environmental factors; continue to use 50 kW of residential micro

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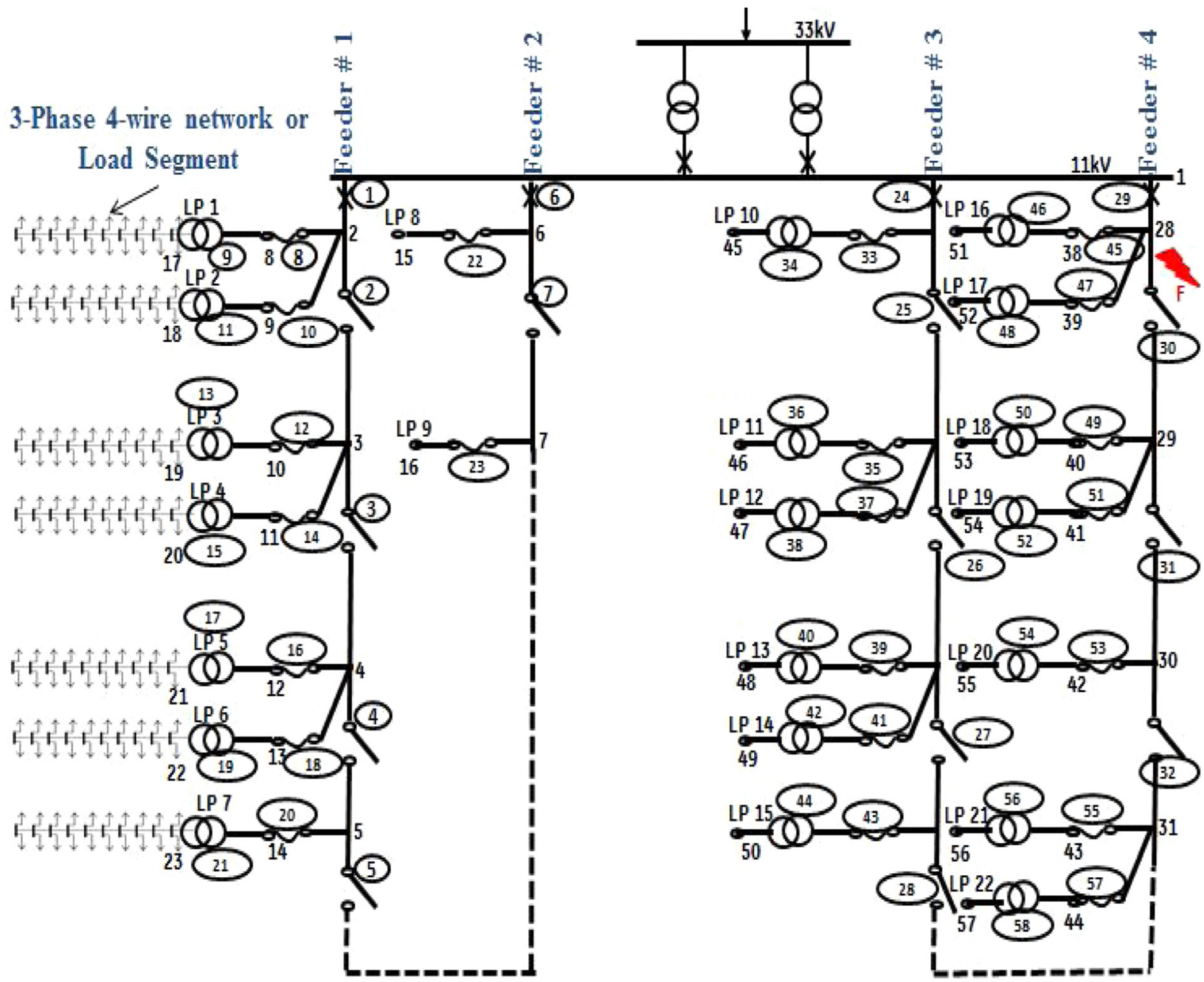

FIGURE 8

RBTS distribution test system.

grid generation available in all three cases reducing the supply power to required level. Monitoring total & concentrations of residential micro grid generation using proposed weighted graph approach helps utilities of type A, whereas utilities of type B may be only interested in total available micro grid generation.

D. Monitoring & preventing reverse power flows

One of the major issues in introducing micro grids is handling reverse power flows in distribution networks. Although few distribution utilities are enhancing protection coordination functions to handle reverse power flows with micro grids, some of them try to avoid these reverse power flows by reducing the net micro grid generation or limiting it to certain X% of rated distribution transformer capacity [26]. With most of the distribution systems being radial in nature, proposed weighted graph approach for monitoring the micro grid generation helps in monitoring & preventing the reverse power flows in radial distribution phase lines as explained in Figure 7.

Consider a line section represented as edge of weighted directed graph shown in Figure 7. By monitoring the condition $I_1 > I_3$ from proposed load flow, for each of the line section represented by edge we can check the possibility of reverse power flow specifically in the edges corresponding to the end of distribution phase lines (As we reach end of radial distribution phase line, supply current reduces due to intermittent load currents drawn at each load bus and possibility of reverse current increases). By controlling the current $PUI = \frac{Maxpowerdifferenceofaphasefromaveragepower}{averagepower}$ in each edge at any instant of time through net meters control capability, reverse power flow can be prevented or avoided.

E. Power restoration

Consider RBTS (Roy Billinton Test System) 33 KV distribution system at bus 2 as shown in Figure 8 [27]. This system has 2 tie switches, 14 sectionalizing switches, 22 load points, 4 Feeders, 22 transformers and 6 circuit breakers. Numbers 9, 11, 13, 15, 17, 19, 21, 22, 23, 34, 36, 38, 40, 42, 44, 46, 48, 50, 52, 54, 56, and 58 represents the distribution transformer load points or load segments. Switch locations 5 and 28 represent tie-switches. A ‘‘Load Segment’’ is defined as a part of distribution network which represents 3-phase distribution transformer (11 kV/400 V) connected to specific feeder and its associated entire downstream 3-phase 4-wire Low Voltage (LV) distribution system.

Load points represented in the above test system are the 3-phase 4-wire distribution systems connected to feeders through 11 kV/400 V distribution transformers. Residential micro grids connect to these low voltage distribution systems like IEEE 33 bus system

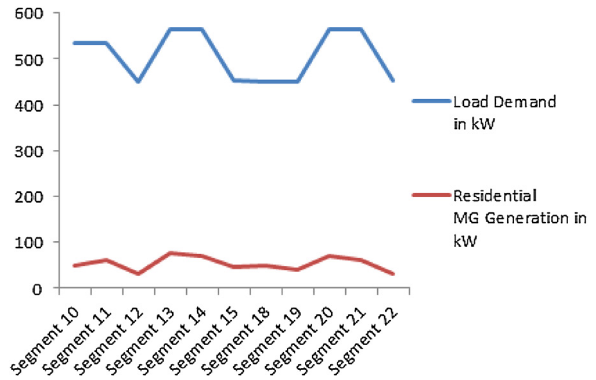

FIGURE 9

Load and residential MG generation data from each segment.

considered for case study purpose. When fault occurs at point 'F' as indicated in RBTS system shown in Figure 8, circuit breaker 29 will trip in order to clear the fault. Based on the fault location identified, auto-sectionalizing switch 30 will be opened in order to isolate the faulted sections which are load segments 16 & 17. Power needs to be restored to load segments 18, 19, 20, 21 and 22 from feeder branch 3 which are affected by fault on feeder branch 4, by closing the tie-switch 28. During this fault condition & associated power restoration analysis following situations can arise based on load demand at that instant,

***Case 1*:** Adequate supply power available to restore power to fault affected loads on feeder 4 from feeder 3 without violating feeder 3 rated over current limits.

***Case 2*:** Adequate supply power available to restore power to fault affected loads on feeder 4 from feeder 3, violating feeder 3 rated over current limits.

***Case 3*:** Adequate supply power is not available to restore power to fault affected loads on feeder 4 from feeder 3.

Load segmentation algorithm demonstrated by authors in Ref. [28] groups the entire distribution system into load segments. With residential micro grids installed in all load segments, total (as shown in Figure 9) & concentrations of residential micro grid generation available in each load segment can be monitored using proposed weighted graph methodology as explained in Section ''Proposed methodology''. DA system operates along with integrated AMI system, analysing distribution system in terms of group of load segments connected to a specific feeder. For effective restoration analysis, these load segments are mapped to its corresponding upstream or downstream feeder sectionalizing or tie switches, using individual asset ID tags of these distribution system components represented in Geographical Information System (GIS) database.

This approach helps in handling power restoration with residential micro grids connected to load segments using net meters more effectively. Such as in case 1, residential micro grids in all load segments of feeder 3 & 4 can be commanded to be disconnected from grid as adequate supply power is available from feeder 3. In case 2, based on amount of power being not supplied due to feeder 3 limit violation, residential micro grids in specific load segments of feeder 3 & 4 can be operated to supply power. In case 3, based on amount of power being not supplied due to supply deficiency, residential micro grids in specific load segments of feeder 3 & 4 can be operated to supply remaining power. Residential micro grid generation concentration monitored in each single phase network of load segment through weighted graph approach in section ''Proposed methodology'', helps in identifying specific net meters that needs to be controlled to derive required micro grid generation output based on power restoration analysis.

Key contributions and constraints

In literature though several methods are being proposed to manage residential micro grids connected to utility grid, they can only monitor & manage the total amount of micro grid generation. With the proposed AMI/GIS based load flow methodology, concentration of residential micro grid generation in each phase of the 3-phase distribution systems can be analysed using weighted graph approach. This graph approach helps in selective control of group of net meters based on concentration of micro grid generation in each line section represented as edge. It will further help to regulate/manage the amount of residential micro grid generation required at any instant of time with respect to the supply power available from utility grid.

From the constraints side, this method requires data to be collected from meters at an interval of 1 to 5 min (configurable) unlike fixed 15 min interval for meter data management systems. Communication redundancy and data priority mechanisms help in handling protocol errors and bandwidth constraints. Historical or estimated data can be used in case of data loss. Advanced smart meters are robust and handle measurement errors at device level. Non-technical losses (any) can be accounted as difference in supply and measured load currents for each phase and forward computation of load flow (section B of appendix) accounts the current due to these losses along with any un-metered loads like street lights while computing the load flow.

Conclusion

There is a definite need to develop technologies which can effectively monitor and control the residential micro grid generation in each phase of 3-phase 11 kV/400 V distribution systems. Proposed method using AMI/GIS features effectively monitors and control the residential micro grids connected to low voltage radial distribution systems based on identifying the concentration of residential micro grid generation in various line sections of single phase network (edges of graph). Identifying & controlling net meters connected at corresponding line sections helps in regulating the amount of residential micro grid generation at any instant of time.

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