Integrating LV Network Models and Load-Flow Calculations into Smart Grid Planning

Gerwin Hoogsteen, Albert Molderink, Vincent Bakker and Gerard J.M. Smit

***Abstract*—Increasing energy prices and the greenhouse effect demand a more efficient supply of energy. More residents start to install their own energy generation sources such as photovoltaic cells. The introduction of distributed generation in the low-voltage network can have effects that were unexpected when the network was designed and could lead to a bad power quality.**

These developments ask for better insight in the effects of a planning for a fleet of households in a network. This paper presents the results of adding network models to planning strategies. Forward-backward load-flow calculations for a three phase low-voltage network are implemented to simulate the network. The results from load-flow calculations are used as feedback for demand side management.

The results in this paper show that the implementation is both fast and accurate enough for integration purposes. Combining load-flow feedback and demand side management leads to improved worst-case voltage levels and cable usage whilst peak-shaving optimization performance does not degrade significantly. These results indicate that load-flow calculations should be integrated with demand side management methodologies to evaluate whether networks support the effects of steering production and consumption. More sophisticated integration of network models are left for future work.

***Index Terms*—Demand Side Management, Distributed Generation, Load-flow Calculations, Network Modeling, Smart Grid.**

I. Introduction

The adoption of alternative sources of electrical energy, such as photovoltaic cells and micro combined heat and power, changes the energy distribution landscape. Most low-voltage (LV) distribution networks were never designed for this ongoing move from centralized energy production to decentralized distributed generation (DG). Voltage rises are possible with the introduction of DG. Without monitoring, it is also hard to tell in which direction current is flowing with DG. Measurements at the transformer might not be enough to guarantee a safe and stable supply of energy to households. Furthermore, introduction of large loads such as heat pumps and electrical vehicles (EV) might require additional investments in networks. New networks are usually overdimensioned to cope with the uncertain future of networks. The higher initial costs mitigate future costs of strengthening the grid. However, a lot of capacity will never be used.

Demand side management (DSM) methodologies are developed to enable grid usage optimization by peak-shaving and matching consumption and production. This reduces the peak power consumption in a grid and enables the use of smaller transformers. Alternatively, the network capacity can be used more efficiently to allow the introduction of more DG. However, these techniques do not make use of the actual physical distribution grid and might lead to a worse power quality in certain cases. To get insight in voltage levels and cable usage, load-flow calculations can be executed to verify whether the grid is operated safely.

Our approach is to integrate network models into DSM in combination with network constraints. The results of load-flow calculations can then be used as feedback by DSM to steer on power quality. This might involve multiple load-flow calculation iterations, so the computational time of the load-flow calculations has to be low. Thus a tradeoff between accuracy and complexity has to be made. These models and load-flow calculations are than integrated in the three-step DSM methodology TRIANA [1] [2]. In addition, more accurate load-flow calculations from an external software tool are integrated. This tool can be used when more accurate results are demanded.

The outline of the rest of this paper is as follows. First related work on relevant subjects is given. Then a brief overview of implementation of load-flow calculations is given. Performance evaluation results are given in the fourth section together with results of integrating load-flow feedback into DSM using a use-case. A discussion on possibilities and implications by integrating load-flow calculations is given in the fifth section. The paper ends with conclusions and future work.

II. Related work

The European norm EN 50160 [3] sets limits to the permitted voltage levels for public supply of electrical energy. Voltage levels at households in the LV networks must be within 10% of the nominal voltage level. For European networks operated at a nominal voltage level of $230V$ this results in a minimum of 207V and maximum of 253V. These power quality regulations are required to prevent damage on equipment.

In [4], [5] research is done on simulating the impact of DG in LV networks. These models are verified using real logged data from a residential area. Results show that voltage rises due to introduction of DG are worst in the end of the network. The simulations show overvoltages, but also voltages as low as 207V at other connections. Nykamp et al. [6] show that introduction of large penetration of heat pumps and electrical vehicles require huge investments when no control is applied. Using DSM, the required network investments can be reduced to support the integration of these loads.

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These developments also lead to different LV network design practices to cope with uncertain future developments. Generally thicker cables are used to minimize chances that these cables need to be replaced in the future. This may lead to unnecessary investments in thicker cables and larger transformers of which the capacity will never be utilized. In [7] the usage of shorter cables is advised as well to support more DG and larger loads. Advanced monitoring of the network is suggested in [8]. Metering enables network operators to detect faults easier, adjust transformer turn ratios and gain insight in currents flowing due to injection by DG.

For existing networks it is unknown how much capacity is left for integration of more DG or large loads. In [9] rather conservative estimates for determining the capacity are given based on known consumption levels, rather than actual network capacity. Network capacity is left unused as a result. Better control, models and simulations of future and existing networks can help to decrease required investments or utilize existing infrastructure more efficiently.

In [1] research is done on a three-step planning methodology for smart grids, for which a simulator is implemented [2]. No knowledge of the network is available in this simulator, however. Therefore, the first step is to integrate a model of the LV network. In [10] models for network components that are often used with load-flow calculations are given. These branches represent the cables and are modeled using a pi-model. Loads and generators are connected to the nodes using PV and PQ buses. The active power and voltage values are known for the former type of bus, whereas for the latter the active and reactive power values are known. A slack bus is used to produce or consume energy in the network and set reference voltage levels.

Several load-flow calculation algorithms are suitable for LV networks. Results in [11] and [12] show that the forward-backward sweep algorithms are simple in terms of complexity and require the least amount of floating point operations. The variant where voltage levels are updated in the forward sweep and currents are updated in the backward sweep performs best. Other variants of the forward-backward sweep, such as updating voltage levels in the backward-sweep as well, require more computational time despite the fact that they might converge faster. The same is true for other algorithms such as Newton-Raphson and Gauss-Seidel which converge faster in certain scenarios, but require significantly more computational time.

III. Implementation

A typical residential LV network is the target for the DSM approach with load-flow feedback. Transformers between the medium voltage network and the LV network are not equipped with automatic tap changers. The networks consist of a three phase network with a neutral line. The connection of households to phases is usually distributed normally. Furthermore, households can be connected to all three phases as well. Allowed currents by the fuses installed might be as high as 40A. An example of a typical LV network layout is given in Fig. 1

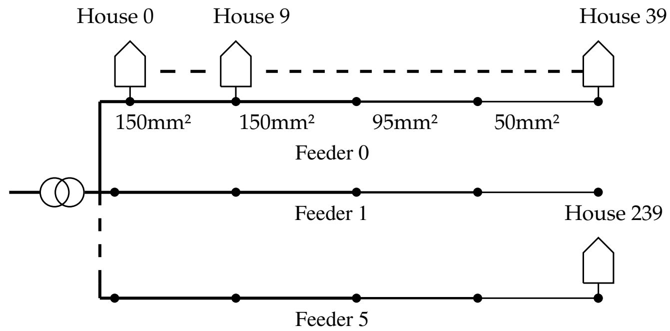

Fig. 1. Typical layout of a Dutch LV network with 6 feeders, usually up to 500m, and 40 connections per feeder. Feeder thickness decreases over the feeder length.

The properties of typical LV networks are exploited for both modeling and load-flow algorithms. As radial operated networks are commonly used, the implementation is optimized for these networks. This allows the use of the forward-backward sweep algorithms that do not require a lot computational time. The simplest form of the algorithm using voltage level updates in the forward sweep and current updates in the backward sweep is implemented. As literature [11] has shown, this is the fastest algorithm with the least amount of complexity. Scenarios where other algorithms perform better, such as low power factor ratios, are not expected in the typical LV networks. The implication is that meshed networks or networks that contain a loop are not suitable for the method presented in this paper.

The network is modeled using a tree structure with branches (representing cables) and nodes. Houses are connected to the nodes using a PQ bus. The PQ-value for each phase for each house is the sum of all power consumed and produced by devices connected to that phase. Individual PV buses for generators are not used since generators in LV networks are required to synchronize their voltage level to the level provided by the grid and therefore a PQ bus with negative consumption can be used.

Before the forward-backward sweep calculations are executed, the voltage levels at the nodes are initialized to the nominal voltage level U_{nom}. For the three phases L1, L2 and L3, these are 230V with a phase angle of -150°, 90° and -30° respectively. Voltage levels are updated during the forward-sweep starting at the node connected to a slack bus, which represents the connection to the secondary side of the MV/LV transformer in the network model. Each feeder originating from the transformer can be calculated independently. Adding identical feeders will therefore result in a linearly increase of required computational time.

The forward-sweep walks over all branches in the tree using a recursive depth-first search algorithm. Consider a network with a node n_1 that is connected to a node n_2 via branch b_1, where n_1 is one branch closer to the slack bus (see Fig. 2). When node n_1 is the current position of the search algorithm, the next step will be to walk branch b_1 to visit node n_2. The rest of the order will force node n_3 to be visited first and then node n_4.

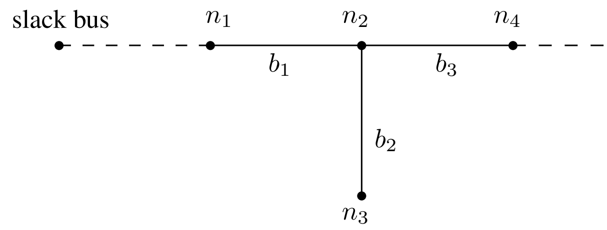

Fig. 2. Part of an example network.

For each visited node n, the voltage level U_n is calculated using the voltage drop U_{drop} over branch b that connects node n and m, with node m being closer to the slack bus:

$$U_n = U_m - U_{\text{drop}} \tag{1}$$

where U_{drop} is calculated using the current I flowing through branch b obtained in the backward-sweep and the cable impedance Z (determined by the resistance R and reactance X) which is represented by the branch:

$$U_{\text{drop}} = I \cdot Z \tag{2}$$

The backward sweep uses the same depth-first search recursive algorithm in reverse order, hence the name. Currents are updated when walking a branch backwards towards the slack bus. The sum of all currents running to or from a node must equal zero. Suppose a branch b being walked from node n towards node m, with m being closer to the slack bus. The current I_b running over branch b towards node n must equal the sum of all currents flowing out $I_{n,\text{out}}$ of node n and the currents flowing to the PQ buses $I_{n,\text{bus}}$ connected to node n. These currents can be obtained by dividing the power consumption (S) through the voltage level obtained in the forward sweep ($I = \frac{S}{U}$). The current I running through branch b is then given by:

$$I_b = \sum I_{n,\text{out}} + \sum I_{n,\text{bus}} \tag{3}$$

The load-flow calculation sweeps are executed until convergence criteria is met. This is tested with the voltage levels at all nodes for all three phases. The difference in node voltage levels U_n between the current iteration (k) and the previous ($k-1$) must be smaller than a predefined error ϵ. For all phases for all nodes in a network the following must hold:

$$\left| U_n^{(k)} - U_n^{(k-1)} \right| < \epsilon \tag{4}$$

This is the basis for implementing forward-backward sweep load-flow calculations. Note that all calculations are done in the complex plane. More details on the models and load-flow calculations can be found in literature ([11], [13] [14] and [7]).

The load-flow calculation is implemented in the TRIANA smart grid simulator [2] using the C++ language. This combination of C++ with the Qt-library makes development easier while remaining portability between different target platforms. Instead of using sparse matrices, the network structure is implemented using objects for nodes and branches in a linked list structure. This results in less memory usage and complexity.

The already existing grid-exchangers for each household are connected to the corresponding PQ bus of the network model. These grid-exchangers pass the total power consumption of all devices connected to it to the load-flow algorithm and are treated as constant power. For each simulation interval the power consumption or production values are obtained. A load-flow calculation is executed to obtain voltage levels and cable usage. These results are fed back to improve the voltage level by altering the planning.

IV. Simulations

This section presents the performance of the load-flow implementation. The used network and house models are discussed in the first section. The second subsection presents simulation and performance evaluation of the load-flow calculation implementation itself. The last subsection consists of a use-case where load-flow results are used as feedback to improve power quality with DSM.

A. Use-case model

The network used for the simulations is a part of an existing Dutch LV network in the town of Lochem. The network files were provided by Dutch distribution system operator Alliander. The network consists of three feeders with a total of 121 households. The length of the feeders is approximately 400m and the feeder thickness decreases over the feeder length. Aluminum cables with cross sections (A) of 150mm^2 (Al 150), 95mm^2 (Al 95) and 50mm^2 (Al 50) are used for the feeder. Each feeder contains about 40 households connected using thinner aluminum cables with a cross section of 16mm^2 (Al 16). The properties of these cables are given in Table I.

TABLE I
Cable properties

Cable type	A (mm²)	R (Ω/km)	X (Ω/km)	I_{nom} (A)
Al 150	150	0.206	0.079	230
Al 95	95	0.320	0.082	175
Al 50	50	0.641	0.085	115
Al 16	16	1.91	0.096	60

These 121 households are modeled after futuristic scenarios by [15]. This model contains households with both controllable and uncontrollable loads and generation with variable penetrations as shown in Table II. Each house has a different configuration and different consumption patterns. One day during the winter is being simulated.

B. Load-flow implementation performance

To evaluate the accuracy of the load-flow implementation, a comparison with load-flow results between the implementation presented and LV network simulator Gaia by PhaseToPhase is conducted. Gaia is the network simulater used by Alliander for designing LV networks. The model of the residential area was made available for this simulator and was converted to a

TABLE II
PENETRATION OF INSTALLED DEVICES IN HOUSEHOLDS

Device	Penetration	Consumption	Controlable
Appliances	100%	9917Wh	no
Smart appliances	100%	2726Wh	yes
Electric vehicles	90%	6587Wh	yes
Heat pump	100%	5715Wh	yes
PV panels	30%	-720Wh	no
8.5kWh Battery	20%	-	yes

configuration file for the implemented load-flow algorithm. A whole day was simulated with 15 minute intervals, resulting in 96 simulations.

The error ϵ is set to 0.00001. The voltage levels converge within ten iterations for all 96 intervals and each simulation takes 1.3ms on average on an Intel Core i5 430M processor running at 2.26GHz. The same simulations take approximately one second with Gaia. The calculated values by the implementation show a standard deviation of 0.50V and a mean deviation of 0.12V compared to the values obtained from Gaia. The maximum voltage deviation compared to Gaia was 1.31V for one single point in the network. The mean deviation of the current is 0.00A with a standard deviation of 0.10A. These results show that the implemented load-flow calculations are accurate enough for integration into DSM. Other parameters not taken into account in both load-flow algorithms, such as the ground temperature, can also lead to errors of this magnitude.

C. *Performance of DSM with load-flow*

One day during the winter is simulated using three settings: no control, DSM and DSM with load-flow feedback (DSM+LF). This DSM+LF is an initial implementation where energy prices at individual households are adjusted using the voltage level feedback from the load-flow calculations after the planning stage. The price is increased with a low voltage level U to encourage production and discourage consumption to increase the voltage level. The price is lowered when the voltage level is high for the opposite effect. Price based steering is only done when the voltage level is not within 5V of the nominal voltage level of 230V. A random number between zero and one (p) is generated to decide whether the price has to be changed or not. This prevents that prices for all houses are increased which can cause overshoots in the steering. The chance that prices change and the amount with which the price changes depends on the deviation from the nominal voltage level and increases with a larger deviation. The following formula is used to calculate with which amount the price will be changed c_{change}:

$$c_{\text{change}} = k * \left(\frac{230 - U}{20}\right) * \left\lceil \left|\frac{230 - U}{20}\right| - p \right\rceil \quad (5)$$

with k being a constant multiplier which is set to 75 units in the simulations. The initial price level is 1000 units. The DSM optimization goal is to flatten the overall consumption profile.

Simulation results show that the mean voltage level (U_{mean}) are comparable with all three settings (see Table III), but that the worst-case voltage levels U_{wc} become worse with DSM compared to simulations without control as shown in Fig. 3. Eight voltage level violations were reported with DSM, where no control resulted in zero violations. DSM+LF improves the voltage levels and resolves the violations introduced with DSM. When looking at the mean network voltage level during the worst case simulation interval, the simulation without control shows the worst results with an average of 223.9V. Using DSM results in an average of 226.0V whereas DSM+LF achieves an average of 226.3V.

TABLE III
SIMULATED VOLTAGE LEVELS (IN V) AND CONSUMPTION FLATTENING RESULTS

	U_{mean} (V)	U_{wc} (V)	η_{wc} (%)	3σ (W)
No control	227.3	210	93.3	203640
DSM	227.2	204	88.5	66111
DSM+LF	227.2	212	66.3	68179

Also the worst-case cable usage (η_{wc}) shows large improvements as shown in Fig. 4. Without planning, the currents in one cable reached 93.3% of the capacity, whilst DSM reduces the worst-case usage to 88.5% due to peak-shaving. Adding load-flow information reduces the worst-case cable usage to 66.3%. In the mean time, the addition of load-flow calculation feedback does not significantly affect peak shaving performance. This performance is measured in 3σ load deviation from the average energy consumption over all simulation intervals (see Table III).

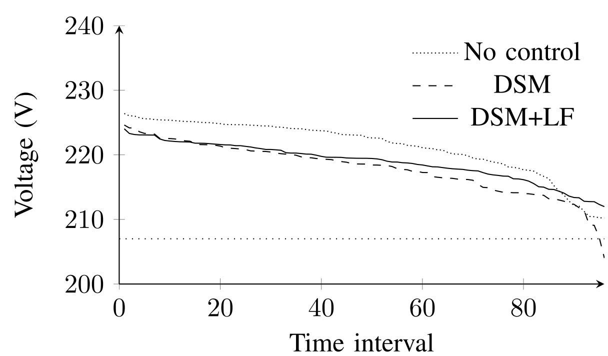

Fig. 3. Voltage level duration curve of the worst-case voltage levels in the simulated network. The dotted line at $207V$ shows the minimum level allowed by the EN 50160.

These results show that DSM decreases the worst-case voltage level and introduces voltage violations due to the lack of network information. The DSM+LF implementation shows a significant improvement in both voltage levels and cable usage compared to DSM and no control, without significantly reducing the peak-shaving performance. Enough flexibility is found in the network to achieve this result.

V. DISCUSSION

The simulation results show that DSM can introduce voltage problems when network layout and properties are not taken into account. The addition of network models and load-flow

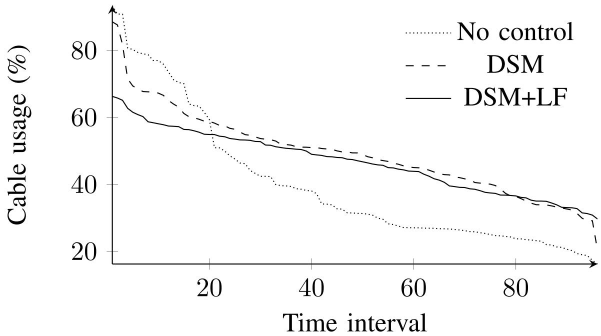

Fig. 4. Cable usage duration curve of the worst-case cable usage.

calculations is therefore advised to verify whether the results of certain DSM methodologies are feasible in realistic scenarios or not. The integration of these models and calculations is not limited to TRIANA.

The current implementation only uses voltage levels from load-flow calculation as feedback. As the voltage level is related to the currents and the cable properties, improving voltage levels also improves cable usage. This is an improvement after the initial planning, however. The network structure yields more options to incorporate network constraints in an earlier stage of planning by adding new planning partitions. These partitions could include balancing production and consumption of a fleet of households that are connected to the same phase or perhaps even the same feeder. From a network structure point-of-view these households are connected closest to each other.

The current approach with changing the prices based on local voltage levels is not a fair method. As voltage issues are more likely to happen at the end of the feeder, the chance of changing prices is higher for households connected at the end. These households have to offer more flexibility to prevent investments in the network that have to be paid by all users. A possible solution to this problem could be to raise or lower the price for all houses connected to a certain phase on a certain feeder depending on the mean voltage level. Another option could be to set a fixed price for the amount of consumption or production that will not cause problems, while the rest is priced differently based on the situation of the network.

Note that changing prices does not give guaranteed grid stability as devices can be active regardless of high prices. To give these kind of guarantees, limits to consumption or production must be enforced. These limits can be lower than the installed fuses in households during certain intervals and depend on local grid constraints. These dynamic limits are possible with smart meters.

VI. Conclusions

Network models and a load-flow calculation algorithm with low complexity are integrated into TRIANA. The results show that the implemented load-flow calculations are accurate. The performance in terms of required computational time is also very good. The results of an initial implementation which combines DSM with load-flow feedback show a significant improvement in voltage levels and cable usage without a significant reduction of peak-shaving performance. Further improvement is required to guarantee compliance with EN 50160 regulations. This may also require hard consumption or production limits to ensure grid stability.

Integration of network models and load-flow calculations enable new optimization goals for planning, such as reducing transport losses and grid investments by utilizing the network more efficient. These goals and implementation improvements are left for future work.

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References

[1] Molderink, A.; Bakker, V.; Bosman, M.G.C.; Hurink, J.L. and Smit, G.J.M., "A three-step methodology to improve domestic energy efficiency," *Innovative Smart Grid Technologies (ISGT), 2010*, pp.1,8, 19-21 Jan. 2010

[2] Bakker, V.; Molderink, A.; Bosman, M.G.C.; Hurink, J.L. and Smit, G.J.M., "On simulating the effect on the energy efficiency of smart grid technologies," *Simulation Conference (WSC), Proceedings of the 2010 Winter*, pp.393,404, 5-8 Dec. 2010

[3] NEN-EN 50160:2010, "Voltage characteristics of electricity supplied by public distribution networks", 2010.

[4] Richardson P. and Keane A., "Impact of high penetrations of micro-generation on low voltage distribution networks". In *Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, pages 1 5, jun. 2009.

[5] Thomson M. and Infield D.G., "Network power-flow analysis for a high penetration of distributed generation". *Power Systems, IEEE Transactions on*, 22(3):1157 1162, aug. 2007.

[6] Nykamp, S.; Molderink, A.; Bakker, V.; Toersche, H.A.; Hurink, J.L. and Smit, G.J.M., "Integration of heat pumps in distribution grids: Economic motivation for grid control," *Innovative Smart Grid Technologies (ISGT Europe), 2012 3rd IEEE PES International Conference and Exhibition on*, pp.1,8, 14-17 Oct. 2012

[7] Oirsouw, van, P.M., "Netten voor Distributie van Elektriciteit". 2012

[8] Kadurek, P.; Cobben, J.F.G. and Kling, W.L., "Future LV distribution network design and current practices in the netherlands". *In Innovative Smart Grid Technologies (ISGT Europe), 2011 2nd IEEE PES International Conference and Exhibition on*, pages 1 6, dec. 2011.

[9] Bollen M. and Hassan F., "Integration of Distributed Generation in the Power System". *Wiley-IEEE Press*, 2011.

[10] Zimmerman, R.D.; Murillo-Sanchez, C.E. and Thomas R.J., "Matpower: Steady-state operations, planning, and analysis tools for power systems research and education". *Power Systems, IEEE Transactions on*, 26(1):12 19, feb. 2011.

[11] Zimmerman, R.D., "Comprehensive Distribution Power Flow: Modeling, Formulation, Solution Algorithms And Analysis", 1995

[12] Eminoglu, U. and Hocaoglu, M.H., "Distribution systems forward/backward sweep-based power flow algorithms: A review and comparison study". *Electric Power Components and Systems*, 37(1):91 110, aug. 2008.

[13] Chen, T.H.; Chen, M.S.; Hwang, K.J.; Kotas, P. and Chebli, E., "Distribution System Power Flow Analysis - A Rigid Approach", *IEEE Transactions on Power Delivery*, Vol. 6, No. 3, July 1991, pp. 1146-1152.

[14] Cheng, C.S. and Shirmohammadi, D., "A Three-Phase Power Flow Method for Real-Time Distribution System Analysis", IEEE/PES 1994 Summer Meeting, San Francisco, CA, July 1994, 94 SM 603-1 PWRS.

[15] Claessen, F.N., "Smart grid control - An analysis of control systems within a Dutch residential microgrid incorporating decentralised renewable energy resources", University of Utrecht, 2012.