POWER TRANSFORMER MONITORING AND AMR SYSTEM SUPPORT FOR COMBINED OPERATION OF DISTRIBUTED RES AND DEMAND SIDE MANAGEMENT

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ABSTRACT

This paper proposes the use of infrastructure of both power transformers MV/LV remote monitoring and automated meters reading (AMR) system as the support for combined operation of distributed renewable energy sources (RES) and demand side management (DSM). The goal is to mitigate some problems, which can occur by intensive apply of strongly fluctuating RES, especially during low-load periods, and to improve the operating regime of networks elements, e.g., power transformers. The proposal of technical solution has been illustrated and elaborated here. The simulation results of its possible apply with supposed RES & DSM program in one particular consumption area have been presented in the paper, too.

INTRODUCTION

By higher penetration of renewable energy sources (RES) with strongly fluctuating (i.e., intermittent, variable) generation into low voltage (LV) grid, can occur the periods with electricity generation greater than the consumption. That would lead to reverse energy flows, towards medium voltage (MV) network, via substations MV/LV and their power transformers. This phenomenon makes the power flows more complicated, it can cause problems in protection relays operation, etc. Beside, during the low-load periods, with the load additionally reduced by the power generation from RES at LV side, power transformers MV/LV operate far away from their optimal regime. To avoid or mitigate such problems, demand side management (DSM) measures, as a kind of energy storage, can be very useful during periods with high RES generation. In this paper, the results of appropriate research have been presented. At first, a DSM program has been modelled, taking into account the fact that indoor temperature rise or fall of 2 ^{o}C can be accepted from the point of occupants' comfort. Hence, if resulting load with RES is too low, some additional devices in households and offices can be switched on, or their operation enhanced, in order to change indoor temperature. Such DSM program has been simulated in a case-study of one MV/LV substation (SS) in Serbian capital, Belgrade, and its consumption area, during peak summer period.

CASE STUDY DESCRIPTION

The goal of the research was to determine the influence of one hypothetical V-RES power plant to the real network's load profile, as well as to investigate possibilities of DSM/DR programs to contribute to load balance, i.e., to perform the role of energy storage.

Network sample and input data

Chosen SS of 1030 kVA installed power is comprised by the Utility's AMR pilot program. However, in the time of our investigation, data recorded by AMR were not sufficient for precise analyses. Therefore, we used instead very reliable data, collected by measuring on MV side, with 15-minutes resolution, from Utility's SCADA. The following approximation has been made: the total load of supplying MV feeder has been divided on supplied substations, proportionally to the rated power of power transformer(s) in each SS.
Dwellings and offices in the area were connected to district heating, or equipped with heat-storage furnaces, and other electrical or non-electrical heating devices.
Another set of input data used for calculations were data about real power generation from an existing PV micro-power plant, at the roof of Technical School „Rade Koncar“ in Belgrade. That plant consists of 22 PV panels, of total installed power of 5060 W. Data with 10-minute resolution were available for the whole 2012. Original measurements were re-calculated for a single PV panel of rated power of 230 W. Normalized values of real electricity generation have been calculated, as the basis for further calculations. Practically, they have been done according to the real insolation during 2012.

Hypothetical PV power plant sizing

To calculate installed power of supposed solar micro-power plant, data about available total roof surface on buildings with customers supplied from chosen SS have been obtained. Roofs were flat mostly, but there were also sloping roofs, even gabled to two or four sides, with skylight windows. The latter fact reduces significantly the possibility of PV panels installation.
Effective surface of cca 2000 m^2 under PV panels seems to be technically feasible. For that value and dimensions (1640 mm x 992 mm) and rated power (250 W) of the chosen single PV panel unit, total installed power of PV micro-power plant would be 375 kW.

Power transformers monitoring system

An original technical solution of device for distributive power transformers' thermal image recording has been presented in [1]. Mathematical model of power transformer's thermal image, applied to estimate its hot-spot temperature has been elaborated there, as well as the block-scheme and brief technical description of realized device, TS-2. Both hardware and firmware solution of the system have been presented in [1].

For several years now, developed prototype of such device operates in real conditions, in one substation MV/LV in Serbian capital, Belgrade. Permanent transmission of real-time measured data have been obtained via GPRS and presented online at official Internet site of Electrical Engineering Institute "Nikola Tesla". Technical solution of remote monitoring has been described in [1], too.

Further development of the device is currently in progress (new type, TS-3) and expansion of the system is planned, to dozens of substation MV/LV in Serbia.

Devices for DSM and apply principles

In households and offices in the chosen area, the use of appropriate devices for DSM has been assumed. Advanced approaches, such those described in [2] and [3], have significant advantages over others, including demand response (DR) based on dynamic pricing and assumptions about the customers' possible reactions. Namely, current DR programs suffer from a collection of market, regulatory, infrastructure and technology problems, such as lack of scalability, lack of privacy, imprecision and non-acceptance by customers, [3].

Two existing thermostats and one novel thermostat have been modelled in [2], to see how well they operate under dynamic pricing. The existing thermostats were a traditional one, with set temperature goals, and a rigid thermostat that minimizes cost while always keeping temperature within a rigid, predetermined range. A novel optimizing thermostat, however, finds the optimal trade-off between comfort and costs. Both theoretical comparison of thermostats' performance and comparison via numerical simulations show that, under plausible assumptions, the optimizing thermostat's advantage is economically large, [2]. Importantly, the electricity demand of the rigid thermostat (but not the optimizing thermostat) ceases to respond to electricity prices on precisely the days when the electricity grid tends to be near capacity. These were the times when demand response was the most socially valuable to avoid massive price spikes. The social benefits of the optimizing thermostat may provide incentives for utilities and regulators to encourage its adoption, [2].

Approach described in [3], called *ColorPower*, is based on service priority tiers for appliances (defined by the customer itself) and on stochastic distributed computing. It can overcome the problems mentioned above and be integrated with energy markets. It takes advantage of inexpensive communications technology to estimate the state of home and small-business major electrical appliances and have those appliances respond to power grid state signals within a few seconds. The capability of *ColorPower* approach to quickly and resiliently shape demand, without exposing customer to either dynamic pricing or coercive load control, presents its main advantage. Hence, it can be integrated with energy markets to achieve the same economic, reliability and balancing goals as dynamic pricing and traditional DR, with superior potential capabilities and without their drawbacks, [3].

The model of DSM program

Particular DSM program, designed for this case study, can use either or both optimizing thermostat and "smart" plugs for *ColorPower* system. They can be used not only when the power distribution system tends to be near its capacity, by switching off some appliances, but also in the opposite case; If the load is too low and/or power generation from distributed RES higher than consumption, some additional appliances of customers can be switched on. Designed DSM program can be represented then with the following expressions:

$$\Delta P = P_{dem} - P_{gPV} + k^L_{Pm\theta} \cdot |\Delta\theta_{\max}| > 0.1 \cdot P^{PT}_{inst} \Rightarrow$$
$$\Rightarrow \Delta P_{dem} = 0.1 \cdot P^{PT}_{inst}\ ; |\Delta\theta_r| = 2\ ^oC \qquad (1)$$

$$\Delta P = P_{dem} - P_{gPV} + k^L_{Pm\theta} \cdot |\Delta\theta_{\max}| < 0.1 \cdot P^{PT}_{inst} \Rightarrow$$
$$\Rightarrow \Delta P_{dem} = \Delta P\ ; |\Delta\theta_r| = \frac{P^{AC+}_{dem} - P_{dem} + P_{gPV}}{k^L_{Pm\theta}} < 2\ ^oC \qquad (2)$$

where:

P_{dem} – original, recorded demand load, with normal engagement of air conditioning devices,

$P_{dem}{}^{AC+}$ – calculated demand load, with enhanced engagement of air conditioning devices,

P_{gPV} – possible generated power from PV panels, installed in analyzed consumption area,

$k^L{}_{Pm\theta}$ – the slope of the linearized function of daily peak load vs. average daily temperature: $P_{md} = f\,(\theta_{av}{}^a)$,

$|\Delta\theta_{\max}|$ – the range of indoor temperature change (2 ^{o}C),

ΔP – calculated sum of the difference between P_{dem} and P_{gPV} and the multiple of $k^L{}_{Pm\theta}$ and $|\Delta\theta_{\max}|$,

$P_{inst}{}^{PT}$ – rated power of power transformer(s) installed in substation MV/LV under consideration,

ΔP_{dem} – calculated demand load increase, expected to be achieved in reality,

$\Delta\theta_r$ – calculated indoor temperature change, expected to be achieved in reality.

The concept of integration

To realize effectively such a program of combined DSM and variable RES, we propose the use of infrastructure of both power transformers MV/LV remote monitoring and automated meters reading (AMR) system. Both systems are still in experimental (pilot-project) phase in Serbian capital, Belgrade, but results achieved are promising, also for supporting described DSM program. Technical solution of their integration has been illustrated here, in Fig. 1.

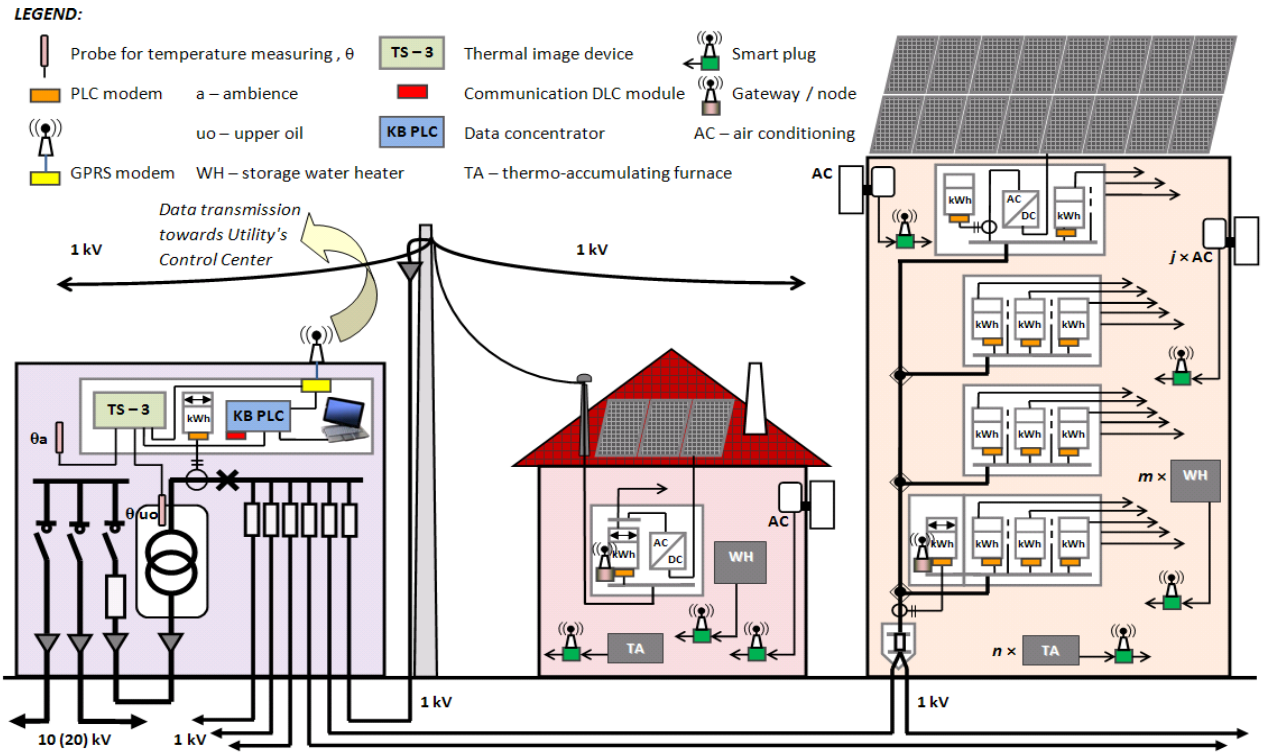

Figure 1 Elements and structure of integrated concept of MV/LV power transformer monitoring, AMR system, demand side management and power generation from intermittent RES

TECHNICAL SOLUTION

Fig. 2 ÷ 4 show the entire system, which integrates automatic meters reading (AMR functionality), monitoring of MV/LV power transformers' thermal images (TS-3 functionality) and remote customers' consumption control (DSM functionality). It has been envisaged that the system has the possibility of monitoring/control of several dozens substations MV/LV and the customers supplied from them. Communication with substations is realized via GSM network, using GPRS service. The use of TCP/IP protocol allows completely independent and separate processing of each substation and its consumption area, as it is shown in Fig. 3. Substation *n* is processed by the fragment (part) *n* of the central SCADA application.

Each part of SCADA application, correspondent to one substation and its consumption area, contains implemented within itself several functionalities and parts, Fig. 4. They are: communication, AMR, TS-3, DSM and a funcionality for storing the read data.

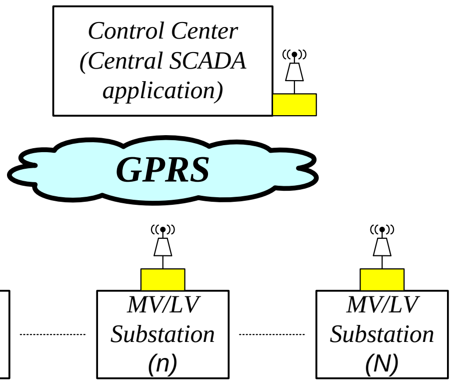

Figure 2 Principle set of the entire system, which includes *N* substations MV/LV

Communication functionality

Communication part of software functionality is used to establish communication with remote devices (KB PLC and TS-3) in substation, and with DSM devices throughout the consumption area. The communication with the latter is realized via PLC modems, Fig. 1. Communication with remote devices is performed periodically, at the moment $t_k = k \cdot T_{\mathrm{cycle}}$, $k = 1,2,\ldots,m$. This communication is realized within strictly defined time slots (Time Division Multiple Access), Fig. 5, during one reading cycle, length of T_{cycle}. Concentrator KB PLC communicates with meters (of total number K), and this communication is performed through LV network (period (t_k, t_A)). During period (t_A, t_B) central SCADA reads the data collected from the consumption area by the concentrator. During period (t_B, t_C) central SCADA reads data from TS-3 device, and this communication can be realized via concentrator, too, Fig. 3. During period (t_C, t_D) central SCADA reads data or send commands to Gateway/Node devices (there are pieces of L, which perform DSM functionality). By that, the concentrator has the bridging function (operates as a communication bridge) between GPRS and PLC communication path. During the period (t_D, t_{k+1}) there is no communication, and the length of that period determines the capacity for adding new meters or Gateway/Node devices.

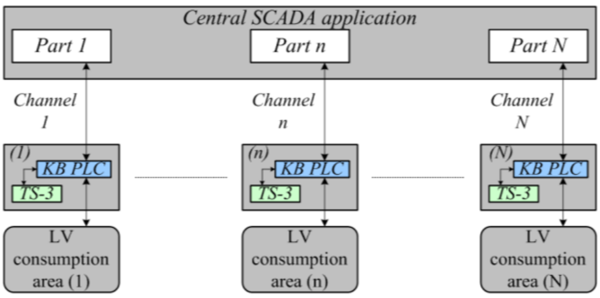

Figure 3 The structure of the central SCADA application and hardware devices installed in SSs

AMR functionality

It performs data processing, read by concentrator, and their placement in the cache (RAM) and permanent memory (database).

TS-3 functionality

It follows the operation of TS-3 device, which "records" the thermal image of supplying power transformer, according to the model described in [1], in details. Data about currently reached power transformer's load, become crucial input for further step, DSM procedure.

DSM functionality

Based on collected data, this part estimates the system behaviour in the next period. If it is necessary, it designs a strategy to overcome the problems (described in the Introduction) and generates the commands to be send to Gateway/Node devices in the next cycle ($Period_{k+1}$).

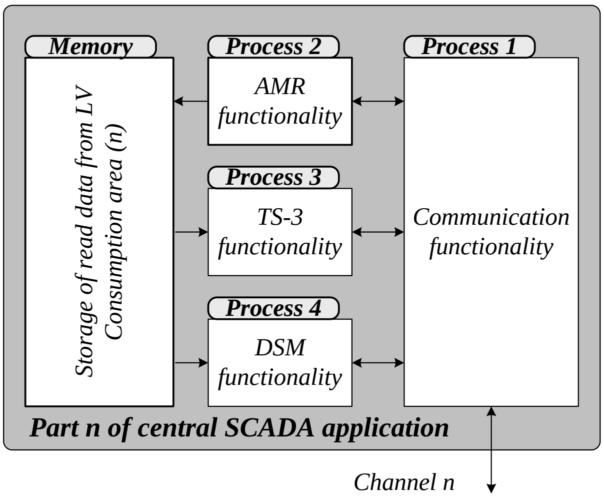

Figure 4 The structure of the central SCADA application fragment related to the consumption area n

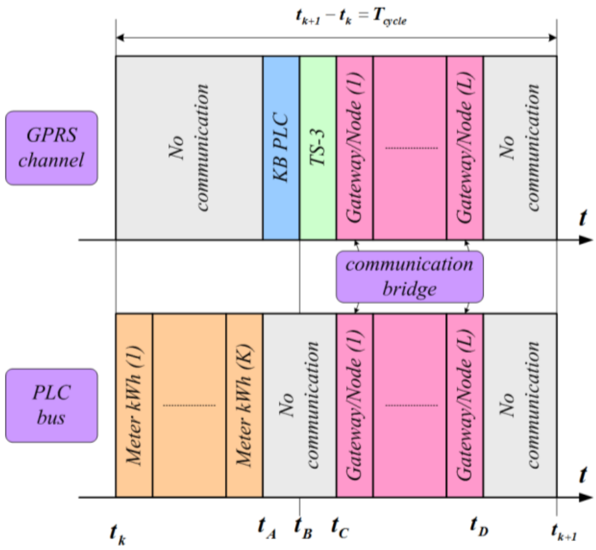

Figure 5 Communication cycle, during $Period_k$

SIMULATION RESULTS

The case-study simulation has been based on real-time, measured input data and DSM model described with (1) and (2). It has been performed for the application of 300 to 1500 PV panels (250 W each), in discrete steps of 300, installed within the consumption area under consideration. The number of PV panels has been varied in order to analyse their influence on load balancing and power losses reduction. Just one, typical, set of results of the simulation has been presented by Fig. 6.

The balanced load profile has significantly smaller fluctuations than original load profile without variable RES, if rated power of installed RES units is up to 30% of annual average load of supplied area. If the share of RES is higher than 70%, fluctuations and slopes of resulting, balanced load profile, rise more intensive.

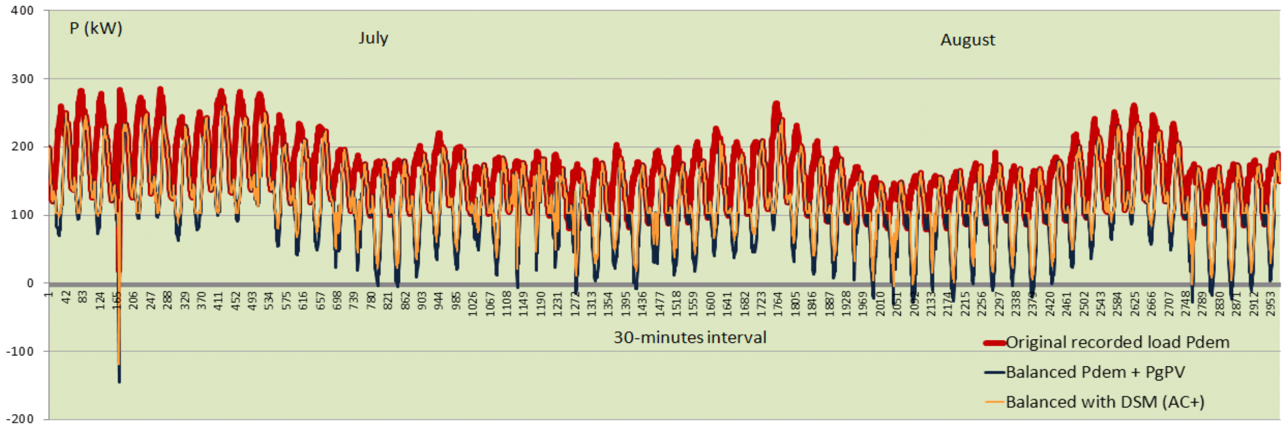

Figure 6 The change of balanced load of substation MV/LV 1030 kVA and generation from 840 PV panels (250 W each); the curve comprising dark parts represents the case without DSM measures

In that case, the apply of some DSM program become very reasonable, reducing that fluctuations and improving the operation of network's elements, Fig. 6.
Calculations showed also that power losses in the grid can be reduced, up to 16%. However, the relative value of this reduction reaches some maximum and with extensive variable RES application that value decreases. Therefore, for each particular case, optimal number of RES units can be determined with the maximal reduction of power losses as the objective.

CONCLUSIONS

DSM/DR measures and programs can play significant role as energy storage, in the grids with strong impact of distributed generation from variable RES. That way, DSM/DR can mitigate power fluctuations and slopes and contribute to optimal network operation, including losses reduction.
The best candidates for DSM/DR programs implementation are customers subjected to Utility's AMR projects, primarily because of existing infrastructure, which allows communication between demand side and Utility's control centre. However, if AMR system is not developed or not reliable enough, for variable RES apply simulations is more accurate to use available data from SCADA at MV level, rather than data from LV side.
Alternatively, or even combined with AMR, the infrastructure of the system for power transformers' remote monitoring can be used for input data acquisition and for two-way communication with DSM devices.
This paper proposed the approach of integrated management of demand, power generation from distributed, highly fluctuating RES, power transformer's operation and metered data. Existing infrastructures of AMR system and power transformers' thermal image monitoring can be used for direct technical support to chosen DSM/DR program. Integration of all functionalities can be performed through extension of existing Utility's SCADA.

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