Stability Improvement Solution of the Smart Power Grid by an Analysis of Voltage Variation in Intelligent Buildings

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Abstract — **This paper describes an approach to minimize the uneven effect of voltage and power in smart buildings and on electrical networks. The analysis is performed by considering diverse scenarios in smart power grids. The idea is to calculate the actual power consumption and power reserves of selected Smart Homes. In a second step, the effect of voltage variation on intelligent buildings and on electrical networks is investigated. In the last part, the control application of Next Generation Network (NGN) and stationary storages for improving the stability, especially those with a high percentage of in-feeds from renewable energy sources (RES) are discussed and evaluated. We consider intelligent buildings or Smart Homes based on Next Generation Network (NGN) components. The NGN components are applied as a communication and integration platform between the smart phone of smart home owners, the home automation and building control system as well as the energy suppliers of the smart power grid. Smart Home appliances based on the KNX bus, the Session Initiation Protocol (SIP) and the Presence Service are used to build a well performing and scalable system based on open source software.**

Keywords - Energy Management, Home Automation;Smart Power Grid, NGN, Presence Service.

I. INTRODUCTION

Intelligent power grids are the core of the future power supply. As a part of smart cities, smart buildings (facilities or houses), smart appliances, smart thermostats, smart meters, real-time dynamic pricing and next-day energy information feedback to electricity users play an important role in this intelligent management infrastructure. Every part of our environment will be connected to each other and can be controlled with the given rights from central points, and to exchange both energy and information. The actual intelligence is the IT-supported structure and control tactics especially to match fluctuating Smart Grids, which are supposed to guarantee stable power supplies within the European Norms. For the stability of a system with a Smart Grid, there are two main criteria: First, the generation has to match the demand at any time and has to hold a reserve (battery storage) for immediate outages. Second, the grid has to provide sufficient capacity for the voltage stability at every portion. According to our particular status and main problems, all countries need to simplify the Smart cities and adjust it to fit their own features. The purpose and relevance of this paper is to describe energy management mechanisms and tactics that include manual and automated control of equipment from uncertain energy sources, and to investigate various issues regarding energy instabilities of the smart building systems. In our consideration, our Smart Homes make use of Next Generation Network technologies (NGN), based on the Session Initiation Protocol (SIP) and the Presence Service [1]. By this way, a near-real-time push solution is realized, using the IP Multimedia Subsystem (IMS) to remotely monitor and control Home Automation systems via mobile devices with open source software. This is described in our previous work [1][2]. According to the latest report by GTM Research, the U.S. home energy management market is forecasted to be worth over 4 billion USD by 2017[3]. This forecast shows the business opportunities and relevance of the proposed document for home control and energy management services. According to this source, the sectors with the biggest potential for saving energy are buildings and mobility.

II. STRUCTURE OF THE PAPER

Following the introduction, Section III shows related work for the suitability of our previous idea to apply a control solution based upon NGN technology. In Section IV, the general concept is outlined and important use cases are presented. The overall system design is described in Section V. The calculation is discussed and evaluated in Sections VI and VII. The components used to analyze the solution are presented in Section VIII. Section IX concludes the paper and gives an outlook of future work.

III. RELATED WORK

Many companies and institutions are working on solutions for energy efficient management for buildings. In our previous work, [1], [2], [13], [17], we presented the detailed idea and hands-on work on operational tools and calculation experiments done on our prototype. The primary idea is to connect the technology of Next Generation Networks (NGN) to Smart Homes. The next step is to use SIP with all its benefits as the main communication protocol and connect it with a bus system standard, in this case KNX [4]. For the home appliances (sensors, actors), a signaling gateway between the KNX home automation and building control system [5] and SIP, allowing communication of mobile devices with KNX sensors/actors using existing SIP infrastructure, is applied.

The focus of this document is to analyze the power instability of NGN based smart homes. In order to meet today's power system requirements; it is the upholding of the voltage regulation within the permitted voltage range in distribution grids on the low voltage and middle voltage level. The consumption of electrical power causes the voltage to drop at the junction point of the smart buildings, whereas injection of power will make it rise. This overshoot-and-dip-effect increases with the power and the distance of the smart buildings to the substation. If the voltage drop or rise gets too high, the distribution system operator has to take counter measures. This is because the end users' appliances and electrical devices are designed for a certain voltage range defined by European norms EN50160:2007 [16]. The amplitude of the supply voltage is defined in the Norm and given in Table I.

TABLE I. TABLE I. AMPLITUDE OF SUPPLY VOLTAGE

Voltage Magnitude	LV: U =230V MV: "by convention"
Voltage Magnitude variations	LV, MV: ±10% for 95% week

It is defined in these norms that the magnitudes of the low voltage and high voltage should be in the given range.

IV. USE CASES OF SMART ENERGY MANAGEMENT

In this section, the uneven effect of two typical use cases of smart energy management, electric load balancing and regulating are discussed.

A. Use case (UC1): Insufficient or lack of renewable energy

In our previous work [1], [2], we discussed that in use case (UC1), the power consumption and load in the city reaches its maximum level. During the same time frame, the feed-in of renewable energy is diminishing to the minimum, e.g., because of wind calm or the lack of sun radiation. Figure 1 illustrates this situation.

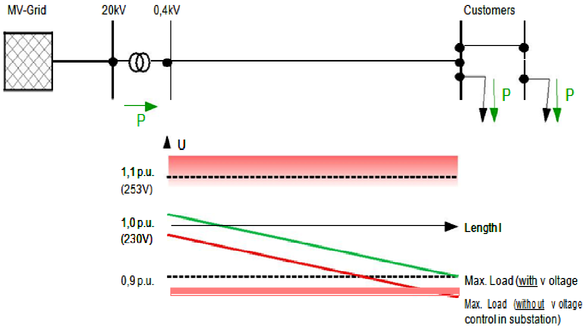

Figure 1. Maximum load scenario

After further analysis on this topic, we have found that in times of high load, the voltage at the terminals might fall below 0.9 p. u. (red line) equivalent to 207 V, which is a supplied or consumed voltage level violation according to European Norm EN50160:2007. This dip effect increases with the power and the distance of the smart houses to the substation. If the voltage drop gets too high, the distribution system operator has to take counter measures. The typical instrument to counteract this effect is the application of tap-changer transformers, because the end users appliances and electrical devices are designed for a certain voltage range defined by European Norm. This lack of electric power shall be balanced with an optimum approach at least partly by the intelligent buildings of the city. In order to do that, the lack of energy is signaled by the power providers towards the owners of intelligent buildings in the city by means of usual communication technologies. The house owners can then react by turning off domestic appliances (e.g., white goods), set air conditioning units or heat pumps into eco-mode and deactivate charging stations for electric cars and vehicles. Therefore, the energy supply within the city could be balanced in a better way by the swarm behavior of the intelligent consumers by de-activating power loads.

B. Use case (UC2): Surplus or excess of renewable energy

In our previous work [1], [2], we also discussed that in (UC2), the power consumption and load in the city reaches its lowest level. During the same time frame, the renewable energy is fed into the power grid at maximum levels because of strong winds or strong sun radiation. Figure 2 illustrates this situation.

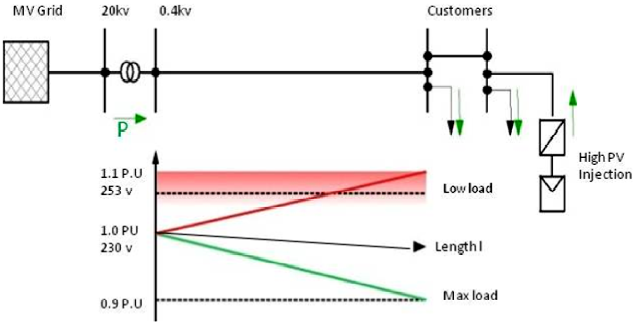

Figure 2. Low load scenario

In times of high Photo voltaic (PV) injection and low load, this is likely to occur in the morning hours. High Photo Voltaic (PV) injection shown here is just to sketch the idea of getting more power from the grid to the consumer. Injection of power may make the voltage at the terminals rise up to 1.1 p.u. (red line), equivalent to 253 V, which is also a possible voltage violation according to European Norm. This overshoot effect increases with the power and the distance of smart houses to the substation. If the voltage rise gets too high, the distribution system operator has to take counter measures, because the end users appliances and electrical devices are designed for a certain voltage range only (as above). Again, this surplus or excess of electric power shall be used with optimum approach by the intelligent buildings of the city. In order to do that, the surplus of energy is again signaled by the energy suppliers towards the owners of intelligent buildings in the city. In this case, a smart phone app is used. The house owners with a smart phone application can react by turning on additional power loads such as domestic appliances (e.g., white goods, air conditioning units or heat pumps), as well as electric cars and vehicles. Also in this case, the energy supply within the city could be balanced by the swarm behavior of the intelligent consumers.

V. CONCEPT AND OVERALL SYSTEM DESIGN

The core concept is to minimize the uneven effect of smart buildings on electrical networks and on the smart power grid, by analyzing and controlling the load profile of the intelligent buildings. The use of information technology allows to improve how the electricity travels from the power grid with power system stability to consumer consumption integration. The basic idea is to balance loads in power grids by using KNX-enabled Smart Homes and a communication infrastructure based on NGN technologies and the Presence Service. The advantages of Next Generation Networks are used to build a communication platform between mobile devices and an intelligent building with a Home Automation solution.

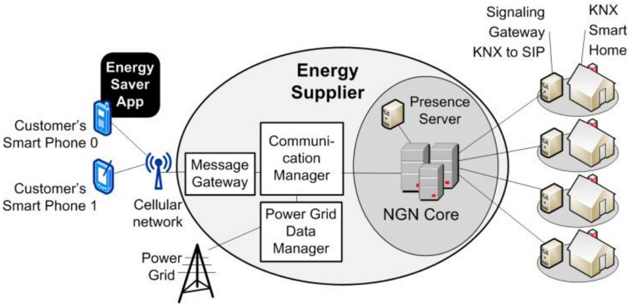

Figure 3. Control system with smart loads L9.....L20

Figure 3 depicts the smart loads and their control system architecture. For simplicity, the loads are named L 9, 10, 19, 20. To analyze the facts related to smart homes and power networks, an integrated engineering tool is used for the power system calculations. The following features are provided by “Dig SILENT Power Factory” [10]: It has been designed as an advanced integrated and interactive software package dedicated to electrical power system and control analysis in order to achieve the main objectives of planning and operation optimization. Some of these functions are load-flow, stability calculation and modal analysis.

To design a Distribution model of a smart home electrical network and a power grid, the following steps have been applied which include the external grid, transformers, bus-bars etc. (see Figure 4.) At first, an external grid (medium voltage) was connected to the bus-bar (B1). The specific bus-bar was connected to a transformer (step-down), the parameters being 120/20 kV. The low-voltage side was connected to the bus-bar (B2). Transformer T1…T3.20/0.4 kV (step-down), the high-voltage end was connected to B2, and the low-voltage end connected to B3. A specific transmission line, one end connected to B3 and the other end to consumer (load), was set up, the Line-Line voltage being 400V and 230 V Line-Ground. There is a total of 12 smart houses and 23 normal houses, resp. Loads (1.14 kW each), power factor 0.95 to bus-bar B3. The transmission line of B3 is 5 km in length. The resistance value for each kilometer of B3 is 0.2215 Ohm, with a reactance of 0.037 Ohm. When voltage is applied to the transmission line (B3), due to different loads, the voltage sags from 400 V to 343 V. The voltage 343 V is not according to the European norms. According to the norms, there can be ±10% voltage magnitude variation of the reference voltage. The distribution grid model consists of five transmission lines, three transformers 0.4 kV, four photo voltaic generators (PV cell) and one motor (battery). Every load at the consumer could be 1 to n number of customers. Three transmission lines are connected to one bus-bar, which is connected to one transformer (20/0.4 kV). The other two transmission lines are connected to a separate bus-bar, which is connected to another transformer (20/0.4 kV). Now, there are mainly two tasks: Energy balancing and operational control. Both tasks

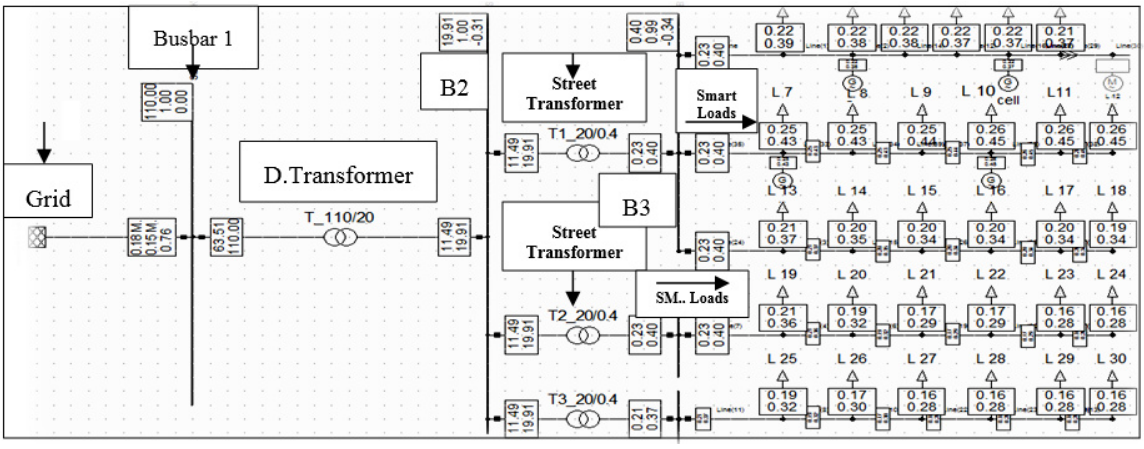

Figure 4. Transmission from Grid to distribution network and transmission from distribution to consumer end

are closely linked, since the power which is generated at different places and times in the grid must be evacuated and transported. According to the German Energy Industry Act, the power from internal Renewable Energy Sources (RES) generators must be evacuated [6]. For further coverage of 30% RES, contracts for RES outside the grid have been made. However, forecast and reality do not always match, neither on the generation nor on the load side [11].

VI. EVALUATION AND ANALYSIS OF THE OUTPUT PLOTS

The scenario being displayed in Figure 5 shows the high load connection. It shows a voltage dip after each load.

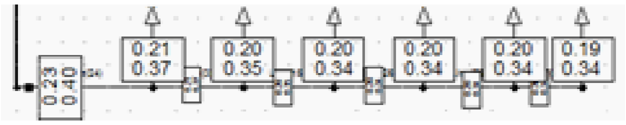

Figure 5. Transmission line with max load smart homes

In Figure 6, the scenario being displayed is high load.

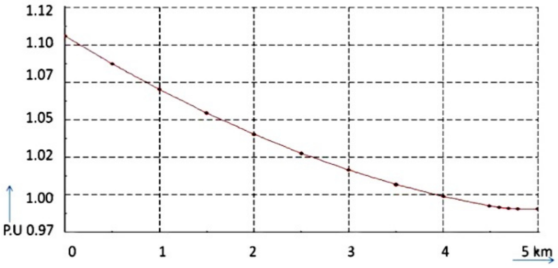

Figure 6. Plot: Voltage drop across supply line, high load at terminals

Given that the voltage has dropped from 1 p.u to 0.97 p.u, equivalent to 207V, at the end of the line. The graph shows that when smart high load is connected on a transmission line, there will be a voltage drop at the consumer end and the effect is increasing when the distance to the substation is increasing. Line-to-Line and Line-to-Phase voltages are reducing drastically. At the end, the voltage variations are violating the Norms. According to EN50160:2007, it should be within the 10% range. Usually, tap-changer transformers are used by distribution system operators as the typical instrument to counteract this effect. The technique is to choose another tap winding, so that the voltage in the substation increases, also affecting the terminal voltage. However, they can only be operated in load-less state which is a great disadvantage. If the voltage is supplied from the grid, the feed-in of renewable energy is diminishing to the minimum and the consumer is in the high load state. The voltage at the transmission line is decreased which has to be improved to a standard according to the Norms. Electrical appliances can be damaged if the voltage levels are not kept within the Norms. The electrical appliances at households cannot bear such decreases in voltage. More current will be drawn by appliances, causing more expenses and affecting the efficiency of these appliances. In the following, the second high Photo voltaic (PV) injection scenario is described (Figure 7). Each load is connected to bus-bar B3 (0.4 kV). Every alternate load is connected via a generator to smart houses.

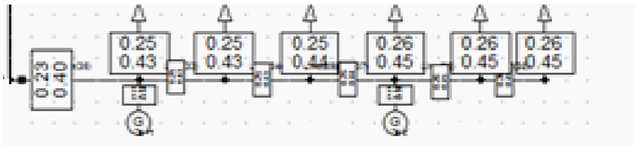

Figure 7. Transmission line with surplus power smart homes

In Figure 8, the scenario being displayed is high integration of in-feed, high Photo voltaic (PV) injection.

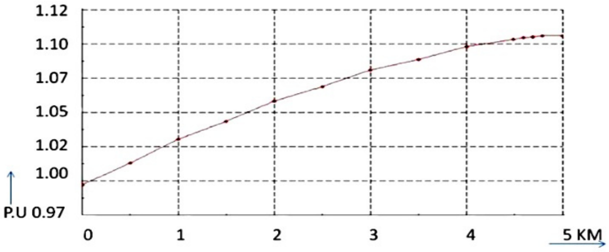

Figure 8. Plot: High Photo voltaic (PV) generation violates voltage criteria

Figure 8 shows the results, in which the voltage increases from 1.0 p.u to 1.10 p.u equivalent to 253 V, at the end of the line. Due to the power injection by the generators (PV panels) on the specific loads, which are connected to that generator, the effect will be distributed and the voltage is increased after every kilometer. Due to this injection of power, the transmission line voltage went high. The system voltage shows an overshoot from normal range, therefore violating the Norms, when excess power is available. Then, compensation should be made. The Photovoltaic (PV) generators (roof of house) are replaced with asynchronous generators, just to implement the idea. The active power of each generator is 0.0045 MW, the reactive Power is 0 MVAr, and the consumer is considered to be a household. If the voltage is now supplied by the grid and the generator injection is applied with the consumer having less load state, the voltage at the transmission line is increased (overshoot), which has to be lowered to a standard according to the Norms. The electrical appliances at households cannot bear such increase in voltage. Damage can be caused to the appliances. Also, the efficiency of these appliances can be affected.

VII. CALCULATION AND EVALUATION

The purpose of this calculation is to find the actual power which is needed to minimize the uneven effect of our smart houses, so an optimal control and balancing technique [1] can be applied. Voltages with U=230V are used as reference. Concerning the given voltage magnitude variations, the admissible voltage range for the LV consumer is 207 V < ULV < 253 V. The terminal voltage is subject to the line impedance R, X and the apparent power, as shown in Figure 9.

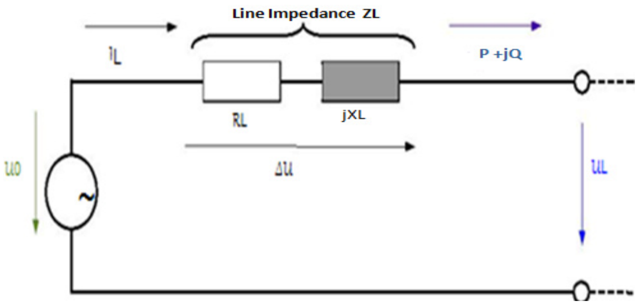

Figure 9: Equivalent circuit of supply line with line impedance

Figure 9 shows the equivalent circuit of a supply line with the voltage U0 at the substation and UL at the junction point to the load. The apparent power S = P + jQ is injected and flowing towards the junction point. The voltage ΔU drops across the line impedance ZL = RL + jXL and can be defined as [12]:

$$U = U_0 - U_l = I \ R_l \ jX_l \qquad (1)$$

Figure 10 shows the voltage across a supply line in the low voltage grid. The flow of the active power P is directed from the MV-Grid downwards through the MV/LV transformer, over a stub line towards the customers. In the following, a calculation of different scenarios (high/low load, high/low PV injection) is presented.

Figure 10. Single line distribution

Apparent power: $S = P + (j \cdot Q)$ (2)

Let Q = 0, then S = P. Number of smart loads = 12.

P/Customer = 1.14 $kW \cdot 12 = 13.68\ kW$

Voltage at Load: $U_a = U_0 \pm U_K$ (3)

Deference Voltage $= U_k$

Voltage at Customer End: U_a = ?

Supply Voltage U_0 = 230V Line-Earth

P [W] = U [V] · I [A]

Current: I = $\frac{P}{V}$ = 13.68 kW / 230 V (4)

I = 0.0594 kA = 59.4 A

Change in Voltage: $U_k = I \cdot Z_k$ (5)

$U_k = I_k \cdot Z_k$

$Z_k = R_k + (j \cdot X_k)$

Resistance = 0.207 Ω / km,
Reactance $X_k = 0.0804$ Ω/km, Distance = 5 km.

$$Z_k = \sqrt{0.5748} = 0.758155 \cdot 5 = 3.79\,\Omega \qquad (6)$$

$$U_k = I_k \cdot Z_k = 59.4 \cdot 3.79 = 225.17\,V \qquad (7)$$

Calculations of specific power:

$$U_k = I_k \cdot U = I \cdot Z_k$$

$$U_a = U_0 \pm U_k = 230V - 225.17\,V = 4.83\,V$$

$$Psp = 4.83 \cdot 59.4 = 286.9\,W \qquad (8)$$

This power is needed to stabilize the transmission line (Figure 11).

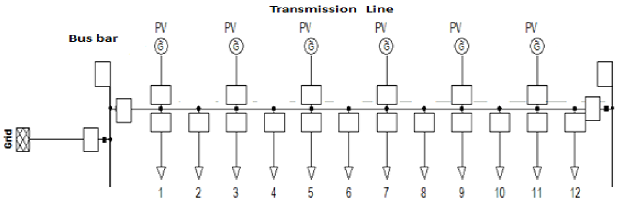

Figure 11.Unloaded Transmission line

Calculation of the excessive and deficit of power as follows:

$$U_a = U_0 \pm U_k = 230\ V - 205\ V = 25\ V = P = 1.485\ kW \qquad (9)$$

$$U_a = U_0 \pm U_k = 230\ V - 253\ V = -23\ V = P = -1.366\ \mathrm{kW} \qquad (10)$$

Figure 12 defines the balanced load profile. Low load and high load scenarios are balanced by increasing or reducing power.

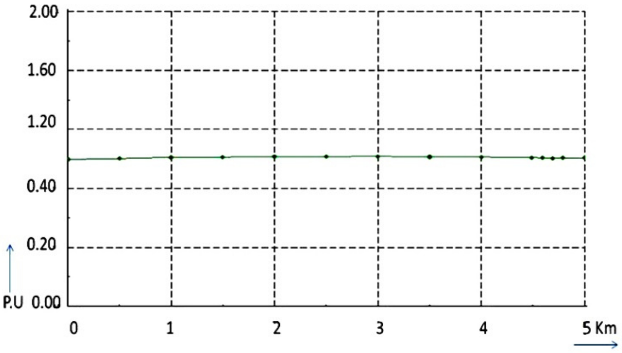

Figure 12. Stabilized Voltage scenario

VIII. COMPONENTS

The following section introduces the components which are needed for the proposed analysis and calculation. The following parts of the workspace are visible: The distribution grid (Figure 13) is fed by an external grid element. The transmission grid has a load element in the middle which represents the distribution grid, as depicted by the red arrow.

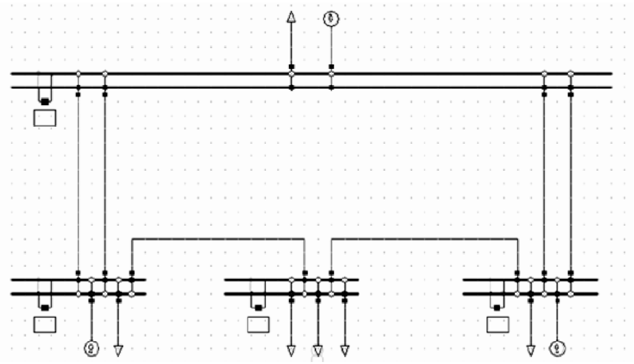

Figure 13. Transmission grid single line diagram

In order to connect the two grids, we have to remove the external net object in the distribution grid, and the middle load element in the transmission grid.

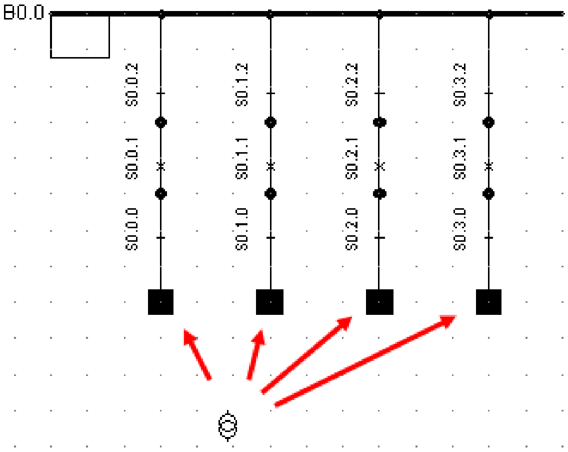

Figure 14. Transformer connected to the single busbar system

To create a 110/33 kV transformer and to connect the 110 kV double bus bar system with the 33 kV bus bar. The terminals (bus bars) of the substations are to be connected with two winding transformers to draw the first transformer, the upper terminal at the position is suggested by the background pattern.

The transformer is now connected graphically to the terminal at that position. The middle terminal makes the second connection (see Figures 14 and 15).

C. Performing a Load Flow Calculation

A load flow calculation may be started from the main menu. For this load flow, the following options need to be set: Calculation Method = AC Load Flow, balanced, positive sequence. All other options on the basic options page need to be disabled [10].

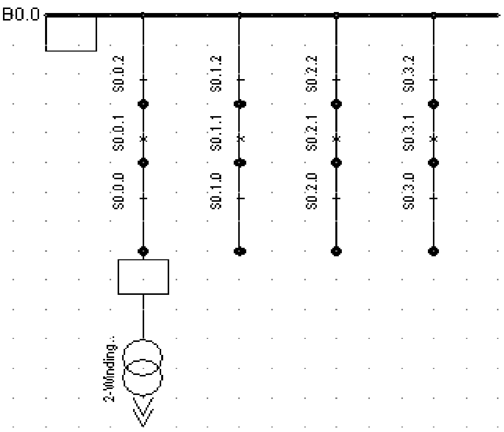

Figure 15. Two Winding Transformer Connection

The load flow calculation is not executed to resolve the error, one should first find the element for which the error was reported. With the Power Factory output window, the error can be corrected and the load flow calculated again.

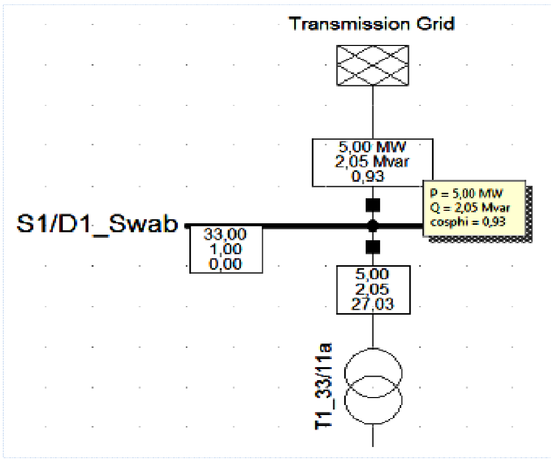

Figure 16. Results of the load flow calculation

Then, the calculation shows that the load flow solving algorithm has found one area (separated area) in the whole system and chosen the external grid element as a reference element. The single line graphic in Figure 16 shows the results of the load flow in the result boxes.

IX. CONCLUSION AND FUTURE WORK

The presented solution enables to analyze the uneven effect of smart houses under the conditions of high voltage and low voltage, when they are not according to the given standard of the EU Norms. Our results evaluate the following important conclusions:

In case of high load and lack of power, and in case of excessive power and low load, we have to manage the certain amount of power which can balance the effect. This could be done by reducing or raising the load with our load management and control solution.

According to our previous work, there is a need of a fully automated appropriate control and load management application with near-real-time push properties, which can respond in real time. This methodic approach could balance the existing smart buildings. Advancements are required in the existing power management systems [18].

An interesting alternative is the integration of battery backup systems. Already a proven technology for uninterrupted power supply (UPS) units, they become increasingly interesting for applications in power systems. They cannot only be used for energy balancing purposes, but can also serve as primary and secondary control reserve. Actually, this concept is not new: A battery-based system was built in Germany for voltage and frequency stabilization for the supply of the island network used in West Berlin 1986. The 17 MW plant / 14 MWh [13] was to going through an entire charge and discharge cycle twice per day.. Keeping in view of the fact if emerging renewable energy sources act as separate generation, they cannot balance the existing energy demand [14]. It is necessary that RES will be integrated in the existing power grid. Due to this integration, the power demands will be balanced at the peak time duration in the grids. This idea will be addressed in future work.

The software being used in this work is a limited version in which only small networks can be analyzed. For future work, voltage variations are to be looked upon at larger scales. This will be done with an extended version of the software, allowing designing a whole city grid model. The number of transmission lines will be increased as well as the number of parameters for the distribution grid. Thus, we will have the knowledge to give an intelligent idea within this remarkable field of study.

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