Co-Simulation-Based Evaluation of Volt-VAR Control

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***Abstract*—The emerging smart grid paradigm enables more efficient use of energy through optimizing the local grid operation. Conservation Voltage Reduction (CVR) is an application which aims at reducing the power consumption by decreasing the voltage level. Another important application is the Volt Ampere Reactive (VAR) control which aims at flattening the voltage profile and improving the power factor, which reduces the losses and eventually reduces the demand. PV solar systems can provide not only active power but also reactive power and hence, they can be exploited by the VAR Control application. Optimized Volt-VAR Control (OVVC) is a combination of these two applications that seeks an optimal coordination of different units to improve the performance of the power grid and save energy. In this paper, we use a co-simulation approach to explore closed-loop CVR and OVVC smart grid applications in a distribution grid. SGsim is a co-simulation framework consisting mainly of the network simulator OMNeT++ and the power grid simulator OpenDSS.**

I. INTRODUCTION

Energy demand in traditional electricity networks has been covered mainly from bulk dispatchable sources and the power flow was unidirectional. The high penetration of fluctuating and non-fluctuating distributed energy resources in the new power grid has created new opportunities and challenges. Therefore, traditional approaches which are based on the considerations of the extreme conditions (e.g. peak load) and the assumption that the voltage drops throughout the feeder are no longer suitable for the new power grid. Meeting the increasing demand through traditional power resources such as oil and coal has become problematic mainly because of environmental and economical concerns. Building new conventional power plants has a bad impact on the environment. Additionally, building new peaking power plants that run only to meet the high demand during high demand periods can be economically infeasible. The situation can be even worse in case of high penetration of highly fluctuating renewable energy resources.

The smart grid paradigm, which represents the integration of information and communication technologies into power systems, allows new communication-enabled applications such as Demand Response (DR), Conservation Voltage Reduction (CVR), and VAR Control. Exchanging information between various devices and managing centers allows better control and coordination among the different units of the power grid and therefore improves the efficiency of supplying and consuming electric power. We have explored the economical benefits of DR in our previous works [2], [4], [6]. In this work we focus on CVR and VAR control at the electricity distribution level. Preliminary results have been published in [5]. CVR is a communication-based application which aims to reduce the energy consumption on distribution feeders by lowering the service voltage. This is based on the assumption that many electric devices draw less power when operating at a lower voltage. In fact, the energy savings depend on the nature of the load. Resistive loads such as incandescent lighting bulbs and ovens are best suited to CVR since the power is proportional to the square of the voltage ($P = V^2/R$). On the other hand, CVR does not guarantee positive effects when applied on loads which draw both real and reactive power such as motors, air conditioners, and compressors. Some of these loads may even draw more power when operating at lower voltage.

The term VAR refers to volt-amperes reactive and describes the reactive power flow in a power system. Reactive power is needed by nearly all system elements and loads without doing any real work. Since the apparent power is a combination of real and reactive powers, the higher the reactive power is, the higher is the apparent power needed to meet a certain load. This results in reduction of system efficiency and increasing of line losses. To reduce the amount of reactive power in the system, electrical utilities usually use capacitor banks for reactive power compensation. The idea is to improve the power factor by generating capacitive reactive power in order to compensate the inductive reactive power.

Volt/VAR Control or VVC refers to the management of voltage and reactive power in a power distribution system. Its main objectives are to maintain acceptable service voltage at all nodes along a distribution feeder and to reduce line losses through power factor correction. This is done by installing and controlling voltage regulation devices such as load tap changers and voltage regulators, and VAR regulation devices such as capacitor banks.

According to [7] there are three approaches to VVC: The standalone approach, the rule-based approach, and the optimization-based approach. In the standalone approach every Volt/VAR regulating device is controlled in an individual and independent manner. Based on local measurements of electrical parameters (voltage, current, power), a capacitor bank is switched on/off or a transformers output tap is changed. In the

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rule-based approach, the regulating devices are monitored and controlled via the Supervisory Control and Data Acquisition (SCADA) system. For this purpose, the devices are equipped with measurement units and communication facilities. Control decisions are taken by a centralized processor, based on a stored set of predefined rules (e.g. ”if power factor less than 0.95, then switch capacitor bank #1 ON”). Typically, the VAR regulating devices are controlled separately from the voltage regulating ones, which results in two independent control applications:

- VAR Dispatch: Control of capacitor banks to correct the power factor
- Voltage Control: Control of On Load Tap Changer (OLTC) and/or voltage regulators to perform conservation voltage reduction (CVR)

Thanks to the communication facilities, the rule-based VVC provides an efficiency improvement compared to the standalone approach. In addition, an alerting system could be implemented to inform about an eventual device failure. However, the operation still does not adapt to changing feeder configuration or varying operation needs since the rules are fixed in advance. In addition, the efficiency improvement is not optimal because the rules for VAR devices are not coordinated with those for Volt devices.

The optimization-based approach aims to provide an optimal coordinated control of all Volt and VAR devices in the system, in order to optimize the utility-specified objective functions. In addition to communication infrastructure, this approach requires a model for the distribution system, and a power flow solver. Real-time measurements and asset changes are regularly transmitted for a synchronized update of the controller. A power flow solution is then applied on the updated system model and the results are sent to an optimizing engine which determines the optimal set of control actions to achieve the desired objective. The optimization approach has a major advantage over the previous two approaches: It provides an optimal efficiency improvement of the system through full coordinated Volt-VAR control. In addition, it adapts well to changing feeder configurations through automatic updates of the system model. Moreover, the presence of the system model and power flow solver allows the integration of distributed generation and a proper handling of the resulting reverse power flows. On the other hand, the main weakness of the optimization approach is the high cost of its implementation and maintenance.

II. Related Work

In [18] four strategies to evaluate CVR effects have been presented. The first strategy is a comparison-based method. There are two basic comparison methods for measuring CVR effects. The first one is to select two similar feeders in the same performance period. The second way is to perform a CVR test on a feeder and apply normal voltage to the same feeder but during another time period with similar weather conditions (control group). The CVR effects can then be calculated based on the measurements from the two tests. In regression-based methods, loads are modeled as a function of their impact factors. In [1] and [12] loads are modeled as a function of temperature. Models for the normal-voltage load process are identified using linear regression, and their outputs are compared with the measured reduced-voltage load to calculate the CVR factor.

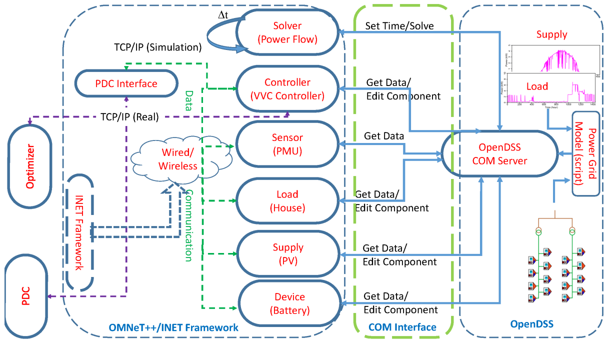


Fig. 1. Structure of the co-simulation framework with the connections between the different components.

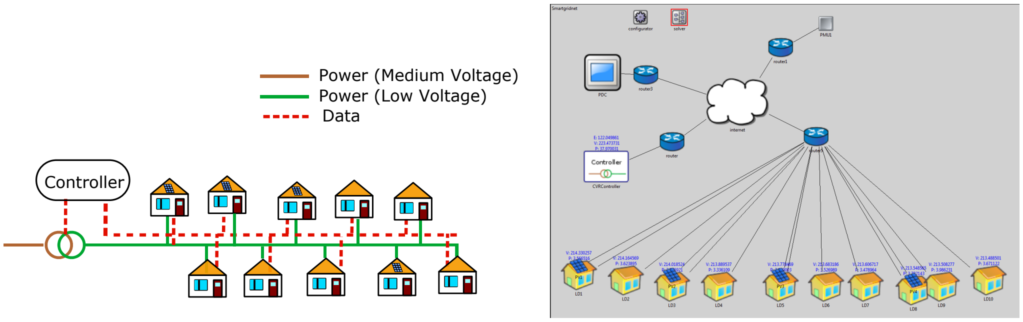
Synthesis-based methods aggregate Load-to-voltage dependence behaviors to estimate the CVR effects of a circuit. There are two ways to perform the aggregation: synthesis from load components and synthesis from customer classes. In the component-based synthesis, the energy consumption of major appliance loads is modeled as a function of voltage, which is identified through laboratory tests. The load shares of each appliance are obtained through surveys.

Simulation methods are based on system modeling and power flow calculation. This method simulates what the load consumption would be if there is no CVR.

Volt/VAR Optimization can be studied on different technical levels. A Mixed Integer Linear Programming (MILP) model for unbalanced distribution feeders is given in [9]. It is formulated in MATLAB and solved with CPLEX. A real-time co-simulated platform is described in [13]. It utilizes the MATLAB OPC Toolbox, the real-time digital simulator RTDS and a real communication platform with DNP.3 protocol, whereas in SGsim the communication platform and the network simulator are implemented in software. Real field trials for Volt/VAR control are presented in [15] for two regions in Austria.

III. Implementation

The co-simulation framework SGsim [14], [3] is based on two main simulators: OpenDSS [11] and OMNeT++ [17]. In addition to a stand-alone executable program, OpenDSS provides an in-process Component Object Model (COM) server DLL designed to be driven from an external program. OMNeT++ is mainly a data communication simulator. Additionally several frameworks, such as the INET framework, have been developed with well-tuned data communication components such as TCP/IP, 802.11, and Ethernet. In order to enable the use of the framework in the field of smart grid applications, we have integrated new components for the electricity distribution network. Figure 1 shows the different



(a) (b)

Fig. 2. Electric power distribution system (a) and screenshot of the simulation environment (b).

components of the simulator. Through the COM interface, it is possible to control the execution of the circuit and to change/add/remove different components.

A. VAR Control

The aim of VAR Control is to compensate the reactive power in the circuit for the sake of a specific objective such as reducing the losses. For this purpose, several components can be used such as capacitor banks, STATCOMs, and inverters. In this paper we focus specifically on exploiting the available inverters which are part of solar systems [16].

B. Conservation Voltage Reduction

In the implementation of closed-loop CVR it is very important to guarantee that the voltage at the end user side is within the acceptable limits. Therefore, each house should send a periodic message of the current voltage as shown in Algorithm 1. If the voltage level at a specific house is lower than the acceptable limit (v_{thr1}), the house sends a warning message. Upon receiving these messages, the CVR controller decide whether to increase or decrease the voltage at the transformer as shown in Algorithm 2.

Algorithm 1 The house application

```
Require: Get Voltage ($V_{hi}$) at house i
Ensure: Send of current voltage value
if ($V_{hi}$) $\leq v_{thr1}$ then
    send a $Under - Voltage$ message to the controller
else
    send a $Normal - Voltage$ message to the controller
end if
Wait one interval long
repeat
```

Algorithm 2 The controller application

```
Require: Receive voltage messages from houses $V$
Ensure: Transformer Output Voltage $v_{TR}$
if $(Normal - Voltage)$ then
    $v_{min} = \min_{v_1 \ldots v_n} V$
    if $v_{min} \geq v_{thr2}$ then
        $v_{TR} = v_{TR} - (v_{min} - v_{thr2})$
    else if $minv \leq v_{thr3}$ then
        $v_{TR} = v_{TR} + (v_{thr3} - v_{min})$
    end if
else if $(Under - Voltage)$ then
    $v_{TR} = v_{TR} + (v_{thr4} - v_{min}) * \beta$
end if
```

C. Optimized Volt-VAR Control

The aim of OVVC is to exploit the available VAR resources to flatten the voltage profile. This way, it will be possible to decrease the voltage at even lower limits than in the case of only CVR and hence this will decrease the demand. Also the power losses will be decreased and consequently the total power consumption will be decreased. At the same time, we have to maximize the usage of the PVs. Thus, the objective function of the optimization problem is to minimize the generation and losses and to maximize the usage of PVs as in Equation 1

$$min\{\sum_{i=1}^{N} P_{Gi} + Losses - P_{Si}\} \tag{1}$$

where P_{Gi} is the power generation at bus i of N buses. This optimization problem is subject to several equality and inequality constraints. The first constraint is the power balance at each bus. The reactive and active power balance at each bus can be written as in equations 2 and 3

$$P_{Gi} + P_{Si} - P_{Li} = \sum_{k=1}^{N} v_i v_k (G_{ik} cos\theta_{ik} + B_{ik} sin\theta_{ik}) \tag{2}$$

$$Q_{Gi} + Q_{Si} - Q_{Li} = \sum_{k=1}^{N} v_i v_k (G_{ik} sin\theta_{ik} - B_{ik} cos\theta_{ik}) \tag{3}$$

Where Q_{Gi} is the reactive power generation at bus i. The P_{Si} and Q_{Si} are the active and reactive power from the solar system. P_{Li} and Q_{Li} are active and reactive load. The v_i is the voltage at bus i, G_{ik} and B_{ik} are the real and imaginary components of the admittance from bus i to bus k. θ_{ik} is the phase shift between bus i and bus k. The loads at the houses are modeled as ZIP loads with the parameters as in Table I

[10]. The ZIP model represents the variation (with voltage) of a load as a composition of the three types of constant loads Z, I, and P which stand for constant impedance, constant current, and constant power loads, respectively. Equations 4 and 5 give the current active and reactive loads as a function of the current voltage (V). The constants P_0 and Q_0 are the design active and reactive power respectively. The v_0 is the design voltage.

$$P_{Li} = P_{0i}\left[Z_P\left(\frac{v_i}{v_0}\right)^2 + I_P\left(\frac{v_i}{v_0}\right) + P_P\right] \tag{4}$$

$$Q_{Li} = Q_{0i}\left[Z_q\left(\frac{v_i}{v_0}\right)^2 + I_q\left(\frac{v_i}{v_0}\right) + P_q\right] \tag{5}$$

The relation between active, reactive, and apparent power at the solar panel can be represented by

$${P_S}_i^{\,2} + {Q_S}_i^{\,2} \leq (S_i^{max})^2 \tag{6}$$

The reactive power is limited by the power design factor

$$-S_i^{max} sin(\phi) \leq Q_{Si} \leq S_i^{max} sin(\phi) \tag{7}$$

The energy losses can be represented as in Equation 8

$$Losses = \frac{1}{2}\sum_{i=1}^{N}\sum_{k=1}^{N} G_{ik}(v_i^2 + v_k^2 - 2v_i v_k(cos\theta_{ik})) \tag{8}$$

The voltage at the costumer side must be within the standardized limits.

$$v_{min} \leq v_i \leq v_{max} \tag{9}$$

The control variables are the voltage at the transformer and the reactive power from the PVs. To implement this approach, each house measures and sends its power consumption to the controller. The controller generates an optimization problem and sends it to a solver. The solver sends back the results. Upon receiving the results, the controller sets the voltage at the load tape changer and sends the set points to the PVs. We have formulated the optimization problem using the general algebraic modeling system (GAMS) and then solving the problem using the solver CONOPT.

IV. EVALUATION

In this section we provide a case study to explore the effect of CVR and OVVC on the demand. The network consists of several houses and PV solar panels connected to a transformer as shown in Figure 2(a). The demand and supply are generated using standard load profiles which provide the active power demand of households as well as other types of loads (e.g. companies and factories). Out of these profiles values are sampled and superimposed with stochastic functions to model the stochastic behavior of a single household such that all houses have a demand of about 5kW and the same load shape

TABLE I
PARAMETERS

Parameter	Value
PV	5 kVA
Z_P, I_P, P_P	0.85, -1.12, 1.27
Z_q, I_q, P_q	10.96, -18.73, 8.77
ϕ	± 0.9
v_{thr1}	212 volt
v_{thr2}	220 volt
v_{thr3}	212 volt
v_{thr4}	215 volt
v_{min}	214 volt
v_{max}	250 volt
β	1.1
r+xj	$(0.320 + 0.075j)/km$
l_1	500 m
l_2	20 m, 100 m

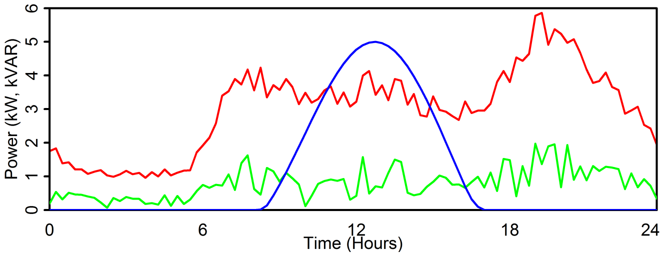
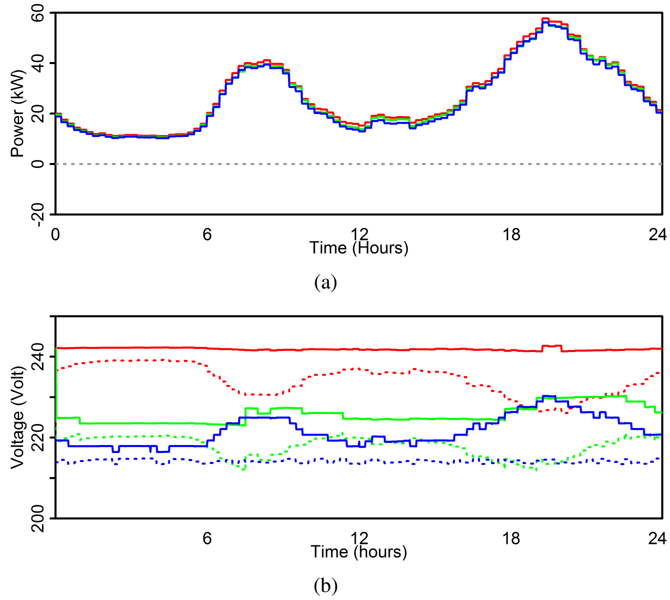


Fig. 3. Demand and supply: active power (red), reactive power (green) and supply (blue).



(a)

(b)

Fig. 4. 10 houses, 4 PVs, 20 m distance between two houses: measured power at the transformer (a) and the voltage at the transformer (line) and the last house (dashed) (b) : without (red), CVR (green) and OVVC (blue).

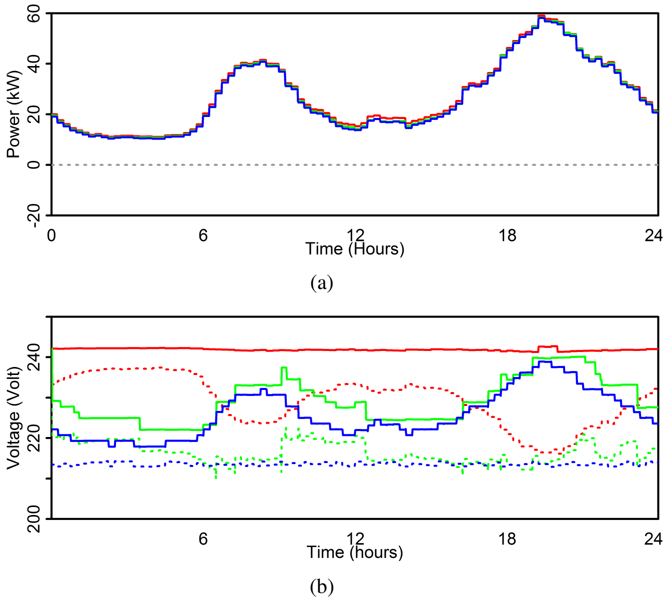


Fig. 5. 10 houses, 4 PVs, 100 m distance between two houses: measured power at the transformer (a) and the voltage at the transformer (line) and the last house (dashed) (b) : without (red), CVR (green) and OVVC (blue).

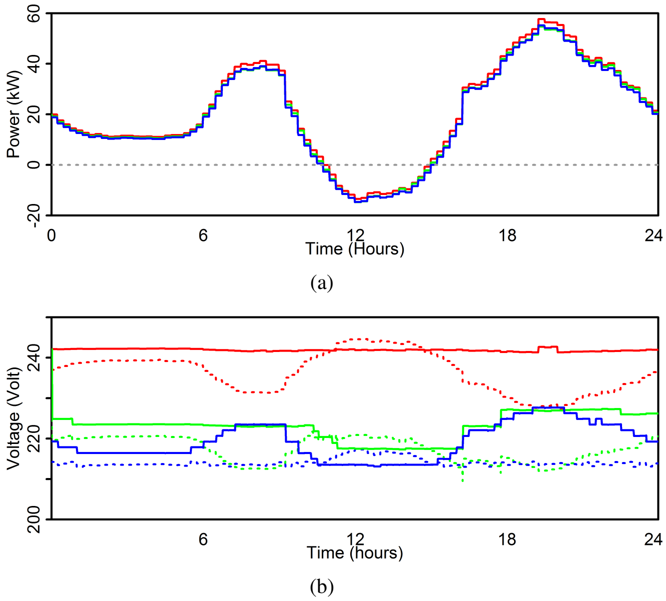


Fig. 6. 10 houses, 10 PVs, 20 m distance between two houses: measured power at the transformer (a) and the voltage at the transformer (line) and the last house (dashed) (b) : without (red), CVR (green) and OVVC (blue).

TABLE II
RESULTS: DEMAND, PERCENTAGE OF REDUCTION AND LOSSES WITH 20 m AND 4 PVS

Approach	Demand (kWh)	Reduction	Losses (kWh)
Without	653.7	-	24.6
CVR	631.4	3.4%	26.0
OVVC	617.6	5.5%	24.0

TABLE III
RESULTS: DEMAND, PERCENTAGE OF REDUCTION AND LOSSES WITH 100 M AND 4 PVS

Approach	Demand (kWh)	Reduction	Losses (kWh)
Without	659.1	-	35.6
CVR	643.1	2.4%	36.6
OVVC	634.0	3.8%	34.3

TABLE IV
RESULTS: DEMAND, PERCENTAGE OF REDUCTION AND LOSSES WITH 20 M AND 10 PVS

Approach	Demand (kWh)	Reduction	Losses (kWh)
Without	508.5	-	22.4
CVR	483.6	4.9%	23.8
OVVC	475.3	6.5%	21.9

but with different values. The standard load profiles do not provide values for reactive power. Therefore, we assumed that the power factor for each house is a random value between 0.95 and 1.0 [8]. The active power (red), reactive power (green), and supply (blue) of a typical house are shown in Figure 3. The model of the first experiment consists of 10 houses and 4 PVs. The distance between the transformer and the first house (l_1) is $500\,\mathrm{m}$ and between two houses (l_2) $20\,\mathrm{m}$. Table I summarizes the parameters. Figure 2(b) shows a screenshot of the OMNeT++ simulation environment in addition to electrical values which have been measured using OpenDSS. The network consists of houses, PVs, controller, PMU and PDC. The voltage at the transformer (V) equals 223 volt, Power (P) is about 37 kW and the energy consumption (E) from the start of simulation is about 122 kWh.

Figure 4(a) shows the power consumption at the transformer with/without applying CVR and with OVVC . The green and red curves show the power consumption with and without applying CVR, respectively. The blue curve depicts the power consumption with OVVC. As it can be seen, the power reduction is higher when the load is high. Table II summarizes the energy consumption during a day for the three approaches. The energy saving is about 3.4% for CVR and 5.5% for OVVC. As can be seen in the table, CVR introduces more losses due the fact that power losses are higher for lower voltage, nevertheless, the whole energy saving is higher than the increased losses. OVVC has a positive impact on the total demand as well as on the losses. An important aim of Volt-VAR Control - in addition to save energy - is reducing the power demand, especially during the peak periods. In fact, CVR can provide ancillary services to the grid, i.e., provide regulation power to maintain balance of supply and demand and alleviate grid stress. This saves utility companies from building addition power plants (i.e., additional spinning reserve). As can be seen in Figure 4(a), at 6 PM, the power difference is about 2 kW. If we scale this value up to a city with thousands of houses, this would mean we can save building a new several mega watt power plant. Figure 4(b) shows the voltage at the transformer as well as at the last house during the day for the three approaches. The traditional approach is based on the considerations of the extreme conditions for peak load and weak load. The OVVC tries to maintain a constant voltage at the end user side so that the demand is minimal. In case of CVR we can see there was a need for low voltage warning messages at about 6 PM. This occur because of sudden increase in the demand. Because the demand is higher than the supply, the voltage at the houses is always lower than at the transformer.

In the next experiment we increased the distance between the houses to 100 m. This causes more voltage drop throughout the feeder. Figure 5(a) shows that the reduction of power consumption in the high demand period is less than the reduction in the previous experiment. This is due to the fact that the long feeder has caused a higher voltage drop and hence, the reduction of the voltage at the transformer was very limited. This can be seen from the voltage value at the last house during the peak period, Figure 5(b). Table III summarizes the energy consumption and losses for this experiment. The increase of losses in the feeders have caused higher demand and hence higher energy consumption. The impact of CVR is better in high density areas.

To study the effect of distributed energy resources on the CVR and OVVC, we increased the number PVs to 10, i.e., each house has a PV. As can be seen in Table IV, increasing the number of PVs has a positive impact on the total demand from the external generator. It has decreased the load by about 6% and 7.7% when applying CVR and OVVC, respectively. Figure 6(a) shows the power flow through the transformer. It is important to notice here that at the noon the power flows in the opposite direction, i.e., from the houses towards the transformer. This happens because at this time the demand is relatively small compared to the supply. Another important observation is that at the midday the voltage at the houses is higher than at the transformer, Figure 6(b). This can lead to over-voltage at the houses which can cause damage. Therefore, the traditional approach is no longer suitable and has to be adapted for situations in which under smart grid conditions bi-directional power flows occur.

V. CONCLUSION

In this paper we have presented a co-simulation approach that enables the investigation of the smart grid application Volt-VAR Control. Through a case study, we have shown the possibility to reduce the energy consumption inside a distribution network by applying a closed-loop CVR. Through message exchange between the houses and the controller, it was possible to reduce the voltage at the transformer. At the same time, the voltage at the end-user side was kept within the acceptable limits. Additionally, we have employed the optimization to exploit reactive power capabilities of solar panels to enhance the savings of CVR and reducing the line losses. The results of the optimization have been fed back into the simulation.

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