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RESEARCH PAPER

Design a Reactive Power Compensator in Smart Home under Variation of Supply Voltage of Low-Level Distributed Power System

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ABSTRACT:

Reactive power compensation is an essential goal for building smart homes when they are supplied from inconsistent voltage sources such as local diesel generators. These houses are subscribing to these generators with limited amperes. While the active power cannot be reduced as home appliances are necessary for daily life, therefore, the focus is on reactive power to be managed. The challenge of dealing with this problem is worsened when the supply voltage is unstable and varies with the time as local diesel generators behave. In this paper, a compensation technique is presented using a modified dynamic capacitor method in which the value of the capacitor is varied and controlled through switching operations. A Matlab/Simulink showed the effectiveness of the proposed technique in compensating the reactive power as well as reducing amperes for different cases of real situations.

KEY WORDS: Smart home, reactive power compensator, dynamic capacitor.
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1. INTRODUCTION:

The essential requirement of the smart home is to have continuous electricity. In some places like the city of Erbil in the Kurdistan Region, Iraq, the power system suffers from supplying customers with continuous electricity due to many factors that impact this insufficiency for many years. Therefore, customers are seeking to have other sources to reparation the deficiency of electricity. Local diesel generators as a major solution are available in almost all areas in the city of Erbil to do this job. Customers subscribed to these generators based on limited amperes. Therefore, household appliances are needed to be arranged according to the availability of the ampere's rating. On the other hand, the majority of these appliances use induction motors (IM), such as refrigerators, different types of air conditions, water pumps, washing machines, etc., which are consuming reactive power from the source. Thus, the reactive power from these types of loads is inductive loads. Reducing the reactive power which refers to compensating leads to reducing the consuming electricity in households, especially in amperes (Nguyen et al., 2022).

Rather than inductive loads, variation of supply voltages from the local diesel generator also impacts the customers. The cause of these variations returns to many factors. When customers' loads increase, the terminal generator voltage will reduce and when loads decrease, the terminal generator voltage will rise. Even though the diesel generators are equipped with an automatic voltage regulation system (AVR), due to mechanical problems of the diesel engine, the VAR may not function correctly especially when these generators are working for a long time, pure maintenance, aging, etc. (Wang et al., 2017, Huda et al., 2019).

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In literature, there are many methods and proposal techniques for compensating the inductive loads. A very basic compensating technique is based on fixed capacitors connected in parallel to main loads. Even though the fixed capacitor is cheap in comparison to other techniques and its fixed value is suitable for many cases, especially in the variation of network voltages, its value increases with increasing the inductive loads which increase the size as well (Sode-Yome and Mithulananthan, 2004). Static var compensator (SVC) is another technique for compensating the reactive power. SVC is a combination of fixed capacitors in parallel with the adjustable inductor. SVC is well in increasing power system stability, improving power factor, controlling overvoltages, and increasing the power transmission, but choosing the appropriate elements and the size are the most issues of SVC (Rao et al, 2009). As a solution to the issues in SVC, a static synchronous compensator (SATCOM) is used (Mithulananthan et al, 2003). SATCOM is a device that converts DC input voltage into AC output voltage for compensating both active and reactive power based on the system status. Although the SATCOM provides dynamic voltage regulation, fast response in reactive power compensation, and high efficiency, but it requires complex control techniques (Zhou et al., 2010).

In comparison to the aforementioned techniques, a dynamic capacitor (DCAP) technique which is based on AC/AC converter, provides dynamic reactive power and harmonic compensations at flexible and low-cost characteristics (Xiong et al., 2018). In general, the DCAP consists of a power capacitor and AC converter (Soori et al, 2021). Due to its economical, reliable, simple, and efficient in low voltage reactive power compensation, the DCAP is used in this research and it is a very good selection in designing smart home reactive power compensation. Another purpose of using DCAP here is its ability to work under variations of the supply voltage.

This work aims to design a reactive power compensation for the smart home that is fed from the main power source at the constant supply voltage and the fluctuated supply voltages of the local diesel generator. The modified DCAP technique is used in the compensation. The range of the capacitor that can be used in compensating the reactive power of inductive loads is based on the pre-estimation of the maximum inductive loads that can operate simultaneously in the house. A Matlab/Simulink is used in designing the whole system for validating the functionality of the reactive power compensation procedure.

The work is organized as follows; an introduction is presented for presenting the goal and background, then followed by the development of the model, which includes a smart home, diesel generator, and DCAP. Then, simulation using Matlab/Simulink is carried out for validating and analyzing the proposed system. Finally, a conclusion is presented in section 5.

2. SMART HOME MODEL

The simplified power system line diagram in conjunction with the local generation that feeds residences is shown in Figure 1, while Figure 2 shows the main parts based on the simulation of the proposed reactive power compensating for smart home that is fed from both grid and local generator. The home as a customer in the community receives electricity from the main power grid, but since the main power grid suffers from a deficiency in covering the entire community with electricity all the time, thus, the grid is subjected to redistribution and shading loads according to the central control program (cut hours program). As a solution for overcoming the grid deficiency, the community will receive limited electricity during cut hours from local generators usually they are diesel machines.

2.1. Power Grid

The power system supplies customers according to the cut program with a constant voltage and frequency. Figure 3 shows the details of the power grid model.

2.2. Transformer

The transmission system transfers the electricity from the generation sites to the customers in different standard high-level distribution voltages according to their distances from the customers. Appliances in homes are working on the base of low-level distribution voltage mainly line-to-earth voltage of 220 Volt (single-phase). Therefore, a transformer is needed for lowering the distribution voltage which is high-level to low-level voltages that is suitable to operate appliances. A step-down transformer model with a short distribution transmission line modeling is shown in Figure 4.

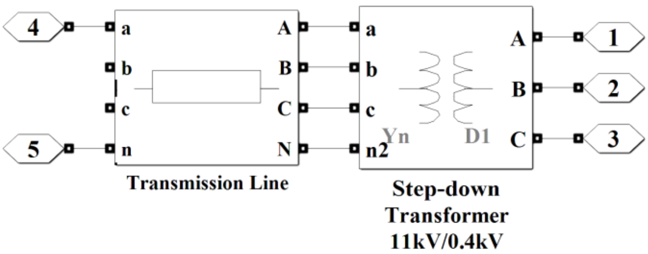


Figure 4: Step-down transformer.

2.3. Local Generator

The local generator represents the diesel generator that feeds up to a few hundred homes within a specific part of the city of Erbil. The rate of generators is varied from 200 KVA up to 1 MVA depending on the number of customers and availability. In this study, frequency variations are assumed to be zero and only variations in terminal voltages are considered. The generator model is

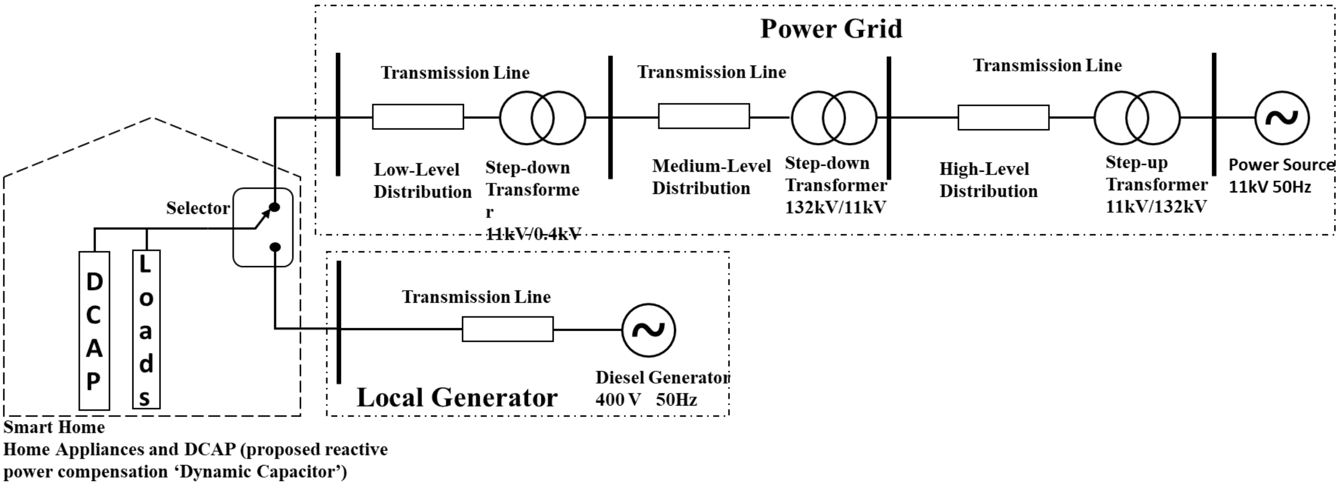


Figure 1: Power system and local generator simplified line diagram.

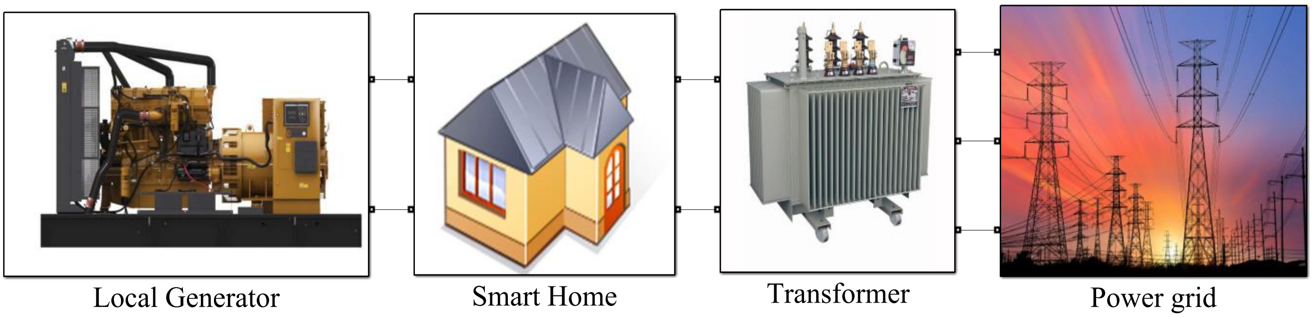


Figure 2: Smart Home Model with local diesel generator and the national grid.

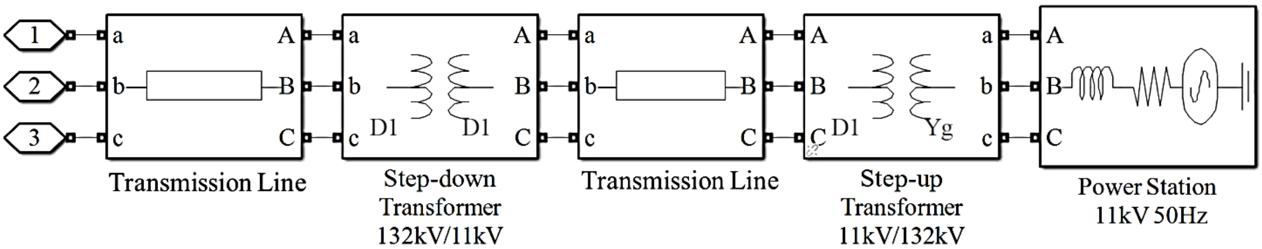


Figure 3: Power Grid.

shown in Figure 5. The generator supplies customers (homes) with fluctuating terminal voltages at a fixed frequency. The generator frequency, in this study, is assumed to be constant all the time at 50Hz.

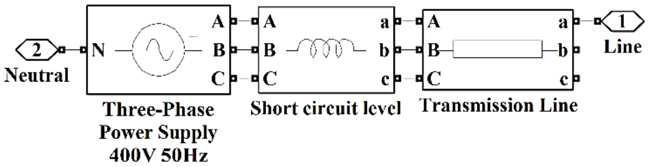


Figure 5: Local generator model.

2.4. Smart Home Appliances

Home is provided with an automatic changeover switching to select between main and local generator as shown in Figure 6. The changeover acts automatically when the main power is available and cut so that the home appliances deliver power continually. Appliances or loads are consisting of different types of home devices such as refrigerators, washing machines, dishwashers, water pumps, boilers, heating and cooling system, TV and other electronic devices, and lights. The majority of these loads are inductive loads as they build with induction motors, therefore, they consume reactive power as inductive loads.

3. MODIFIED DCAP

As mentioned in the previous section, the majority of loads at home are inductive loads which significantly impact the consumption of electricity and degrade the power factor. These directly impact the homeowners by increasing the amperes when they are supplied from the local generator. To eliminate the effect of inductive loads and improve the power factor, the home needs to be equipped with a reactive power compensator namely a capacitor. As this study deals with the variation in supply voltage especially when loads are on a local generator, therefore a static capacitor may not work well in this case. A modified DCAP technique can be implemented for both cases when loads are on the main power grid, at fixed voltages, or on a local generator (variation of voltages). The electric system in the majority of homes is single-phase, therefore, we consider a single-phase dynamic capacitor in this study.

Construction of DCAP

The structure of modified DCAP consists of input voltage v_{in}, the main power capacitor, C, inductor, L, and two switches S_1 and S_2. The two switches are turned on complementary in a specific duty cycle. The DCAP buck and boost converter schemes are proposed in (Sivaganesan et al., 2022) (Chen et al., 2016, Faifer et al, 2021), but in this research, only the boost converter, which is a modified DCAP, is considered and provides sufficient reactive power compensation that can be implemented in any smart homes. The simplification of the modified DCAP configuration is shown in Figure 7.

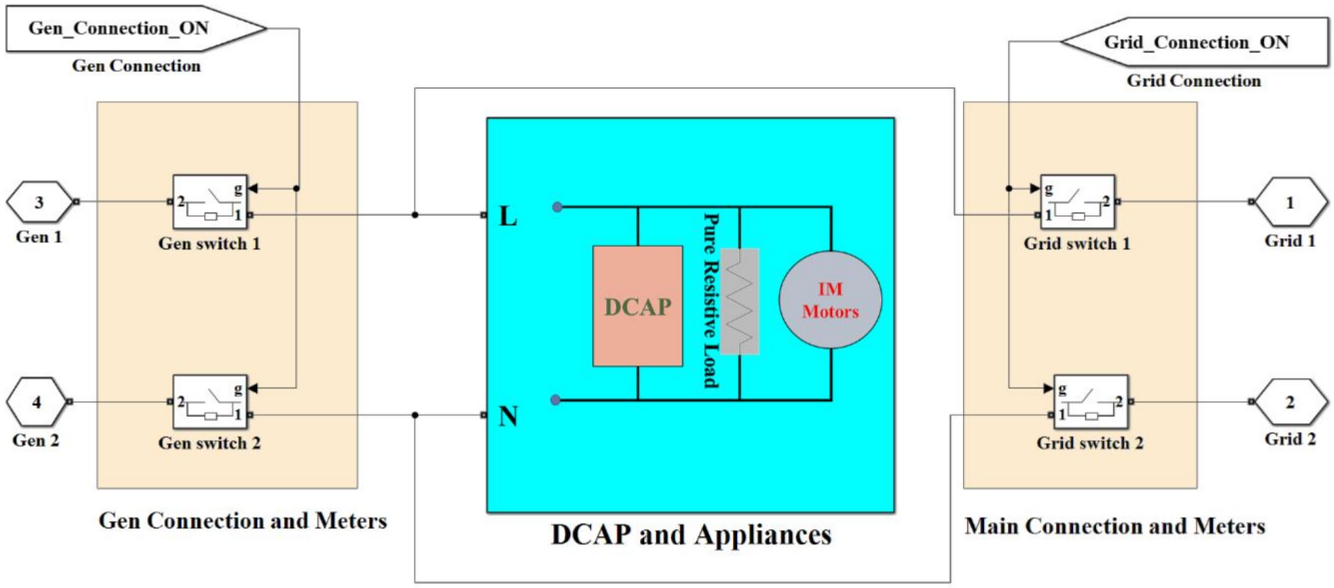


Figure 6: Smart Home DCAP and Appliances.

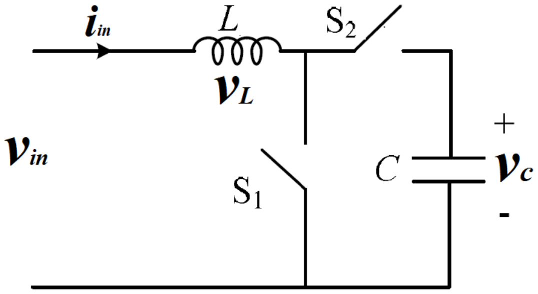


Figure 7: DCAP boost converter circuit diagram.

The two switches work inversely, that is, when ***S₁*** is on (close), ***S₂*** will be off (open), and vice versa within a specific times t_{on} and t_{off}, respectively. Therefore, the duty cycle ***D*** can be defined as:

$$D = \frac{t_{on}}{t} \tag{1}$$

where ***t*** is the cycle time for the operation of both switches: $t = t_{on} + t_{off}$

During the period of S_1 is being on and S_2 is being off, the DCAP equivalent circuit will be as shown in Figure 8. In this case, the following relations can be written:

$$L\frac{di_{in}}{dt} = v_L = v_{in} \tag{2}$$

where v_L is the inductor voltage, v_c is the capacitor voltage and is equal to the previous state voltage.

$$di_{in} = \frac{1}{L}v_{in}dt \tag{3}$$

$$\Delta i_{in} = \frac{1}{L}v_{in}Dt \tag{4}$$

During this period of switch operation, change in input current $\Delta \boldsymbol{i_{in}}$ is positive (increment).

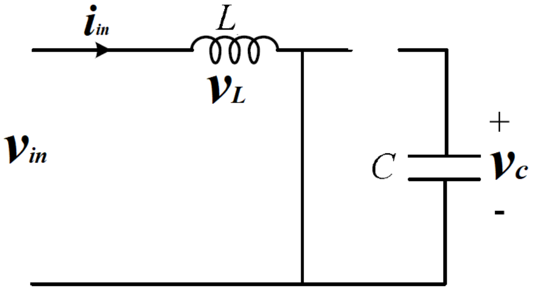


Figure 8: S_1 on and S_2 off equivalent circuit diagram.

During the period of S_1 is being off and S_2 is being on, the DCAP equivalent circuit will be as shown in Figure 9. In this case, the following relations can be written:

$$v_{in} = v_L + v_C \tag{5}$$

$$v_{in} = L\frac{di_{in}}{dt} + v_C \tag{6}$$

$$\frac{di_{in}}{dt} = \frac{v_{in} - v_C}{L} \tag{7}$$

$$\Delta i_{in} = \frac{v_{in} - v_C}{L}(1 - D)t \tag{8}$$

During this period of switch operation, change in input current $\Delta \boldsymbol{i_{in}}$ is negative (decrement).

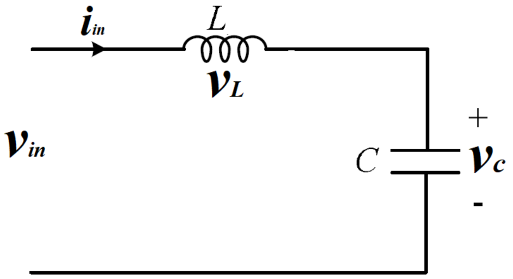


Figure 9: S_1 off and S_2 on the equivalent circuit diagram

Equalizing (4) and (8), yields

$$v_{in}D = -(v_{in} - v_C)(1 - D) \tag{9}$$

$$v_C = \frac{1}{1-D}\, v_{in} \tag{10}$$

Capacitor voltage, v_c, in (8) is a compensating voltage and from (8) the capacitance value will be detected as follows:

$$Q_C = \frac{v_C^2}{X_C} \tag{11}$$

$$C = \frac{Q_C}{2\pi f v_C^2} \tag{12}$$

where Q_C is the capacitive reactive power that is required for compensating the inductive reactive power in home appliances, x_c is the reactance of capacitance, and ***f*** is the system frequency.

The inductor ripple current is twice the inductor current that can be given by (Gupta, 2014)

$$\Delta i_{in} = 2R_f i_L \tag{13}$$

where R_f is the ripple factor of the inductor current.

$$L = \frac{v_{in}}{2R_f i_L}Dt \tag{14}$$

From Figure 9, the capacitor current is the same as the input current and can be found from the following relation:

$$i_{in} = i_L = \frac{v_C}{x_C} \tag{15}$$

where i_L is the inductor current. Substituting (15) in (14), yields

$$L = \frac{v_{in}\, x_C}{2R_f v_C}Dt \tag{16}$$

Substituting (10) in (16), the inductance becomes

$$L = \frac{(1-D)}{4\pi\, f\, C\, R_f} Dt = \frac{D(1-D)}{4\pi f C R_f f_c} \qquad (17)$$

where f_c is the cycle frequency for both switches and is equal to ***1/t***.

4. IMPLEMENTING AND SIMULATION RESULTS

A Matlab/Simulink has been used for implementing the system which was shown in Figure 2. Three different scenarios have been tested. These scenarios include powering home appliances from the main power grid, the generator powering at a fixed voltage, and generator powering in the variation of voltages. Home appliances are based on operating at a distributed low-level voltage of ***220 V*** and ***50Hz***, and they are mixed between pure active loads such as boilers and inductive loads such as motors (as in a refrigerator). For the purpose of this study, the motor is chosen to be a capacitor-start induction machine, however, other types of induction motors also can be implemented. A total load of home appliances is set at ***1400 Watt*** active power and ***1280 Var*** inductive reactive power. Based on this situation, the capacitor and inductive values in DCAP will be computed according to (12) and (17), respectively. For getting the optimum reactive power compensation, the switching frequency is set at ***20kHz***, ripple factor at ***0.2***, and ***D*** at ***0.5***. Hence, ***C*** and ***L*** are ***21.1μF*** and ***4.7mH***, respectively.

Case I

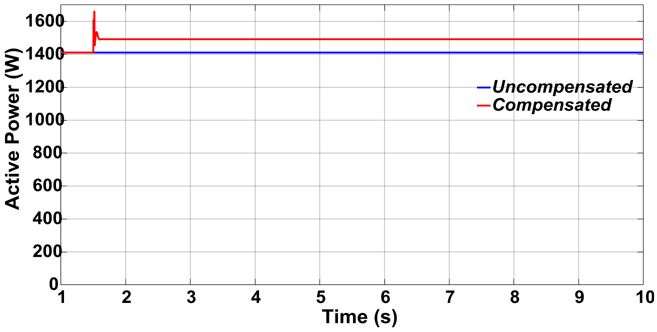
In this case, appliances in the smart home receive electricity from the main source which has a constant voltage and constant frequency, respectively. Compensating of reactive power is programmed to act by using DCAP after ***0.5s*** of operation. Figure 10 shows the simulation results with supplying the main source. From the simulation results, it is clear that the reactive power has been fully compensated shortly after switching on the DCAP to the home electricity. Since the DCAP adds capacitance load to the home electricity, the load voltage has increased as shown in Figure 10 (d). This increase of voltage leads to an increase in the active power which in turn increases the efficiency of those loads that consume active power as shown in Figure 10 (a). DCAP can compensate the reactive power from ***1280 Var*** to almost zero Var as depicted in Figure 10 (b) and consequently the power factor improved to its maximum achievement which is a unity power factor, this is shown in Figure 10 (e). Although the DCAP increases the load voltage and active power, the load current has decreased by ***24.4%***, that is from ***8.905A*** to ***6.732*** A as shown in Figure 10 (c).

Case II

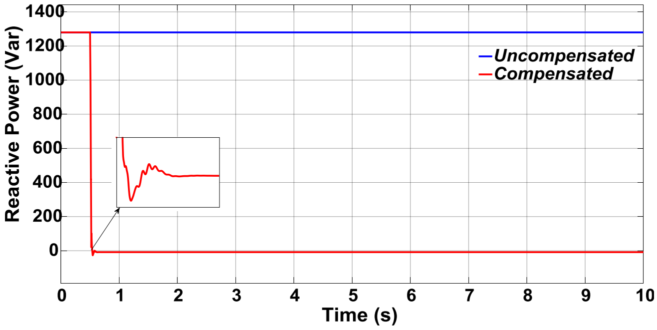
In this case, home appliances receive power from the local generator while the main source has been cut. It is assumed that the local generator operates at a fixed voltage and frequency. Figure 11 shows results for ***case II***. Similar to ***case I***, the DCAP is switched on at ***0.5s*** of operation to unify all cases for comparison. The DCAP increases the load voltage and increases the active power as shown in Figure 11 parts (a) and (d), respectively. The reactive power has been fully compensated to zero Var as shown in Figure 11 (b), and the power factor improved to unity as shown in Figure 11 (e). As with ***case I***, the DCAP decreases load current slightly better to up to ***25%*** which is returned to the nature of the local generator that is closer to the load (Figure 11 (c)).

Case III

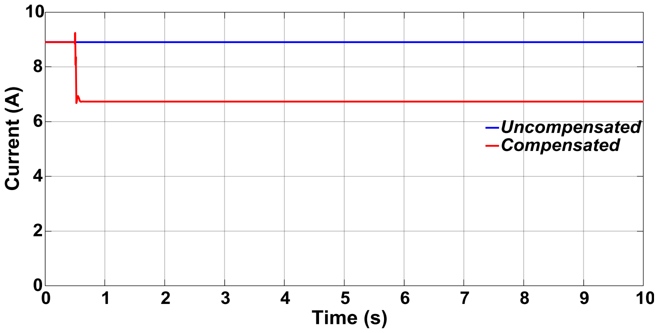
In this case, loads of the home appliances receive power from the local generator that generates power with variable voltage but at a constant frequency of ***50Hz***. The variations of generator voltage are between ***220V*** and ***200V***, and this is close to reality for major local generator performance. Figure 12 (d) shows the generator output voltage variations. The variations of load voltage impact active power, reactive power, and load current, but still, DCAP improves the consumption of the home electricity. Active power has fluctuated with variations of the voltage but it is more when DCAP is adapted (Figure 12 (a)). Contrary to active power, the variations of supply voltage have less impact on reactive power compensating and power factor correction. The reactive power almost is keeping its values around zero (Figure 12 (b)), and the unity power factor (Figure 12 (e)). The load current varies between max ***8.9A*** and min ***8.3A*** when DCAP is not adapted and decreases to max ***6.65A*** and min ***6.35A*** when DCAP is adapted (Figure 12 (c)). On average a ***24%*** decrease in load current has been achieved.



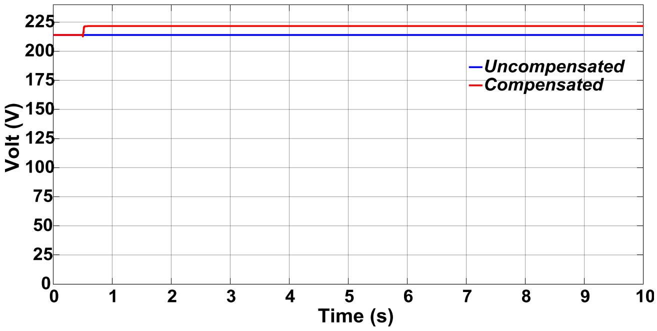
(a) Active power response with and without DCAP



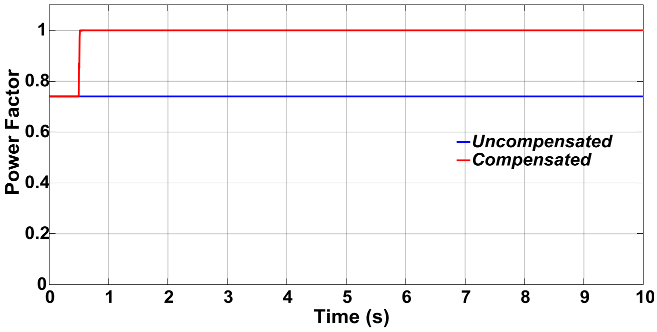
(b) Reactive power response with and without DCAP



(c) Load current with and without DCAP

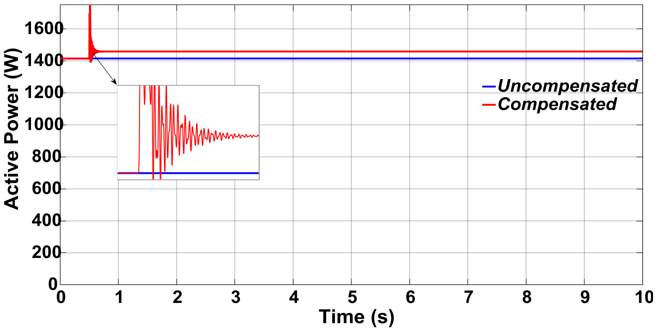


(d) Load voltage with and without DCAP

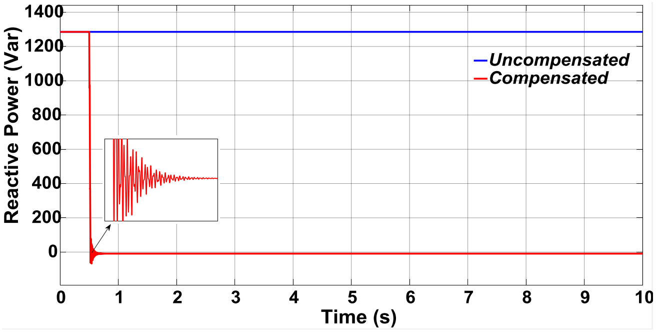


(e) Power factor with and without DCAP

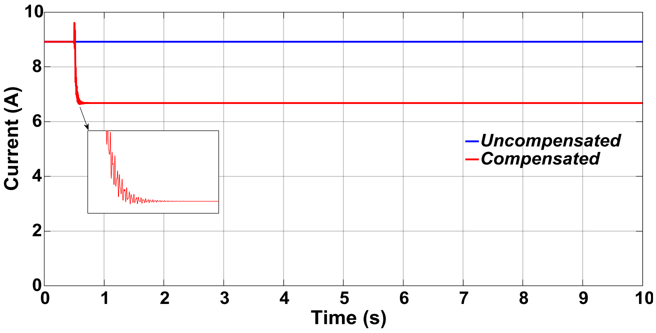
Figure 10: Simulation results when supplying from the main source.



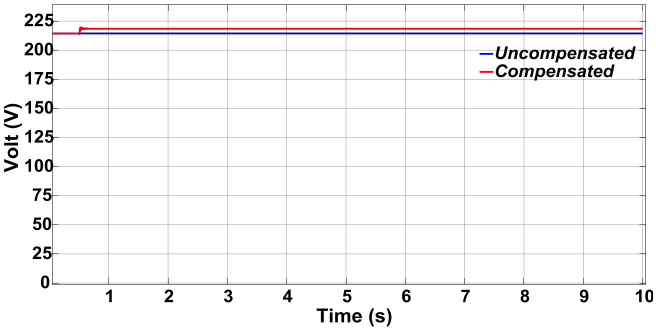
(a) Active power response with and without DCAP



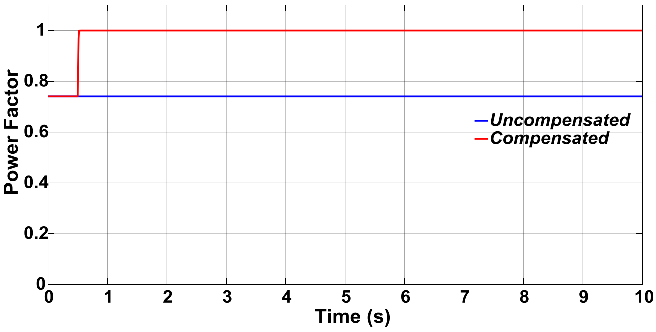
(b) Reactive power response with and without DCAP



(c) Load current with and without DCAP

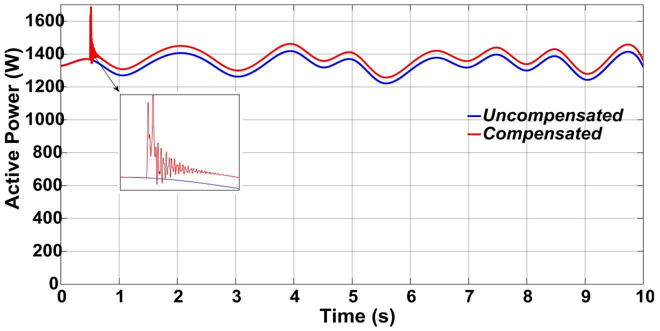


(d) Load voltage with and without DCAP

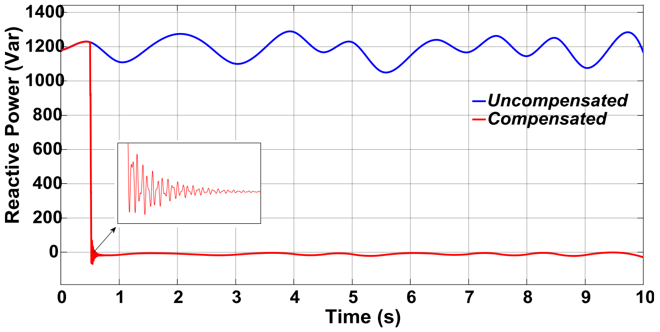


(e) Power factor with and without DCAP

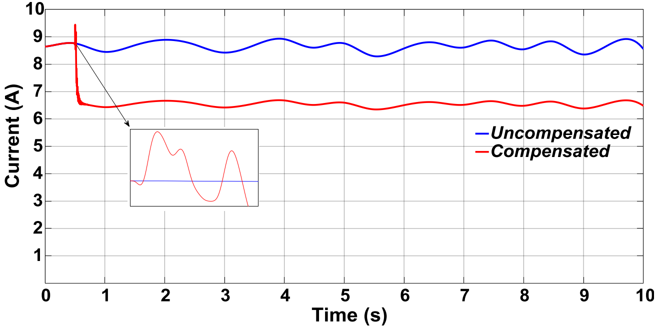
Figure 11: Simulation results when appliances are supplied from an ideal local generator.



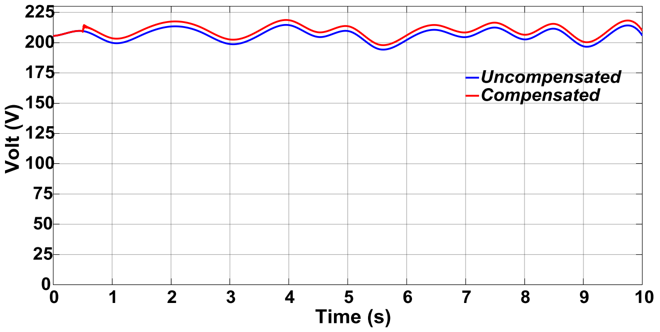
(a) Active power response with and without DCAP



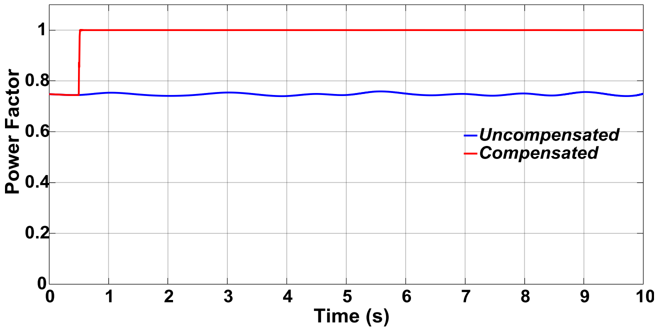
(b) Reactive power response with and without DCAP



(c) Load current with and without DCAP



(d) Load voltage with and without DCAP



(e) Power factor with and without DCAP

Figure 12: Simulation results when supplying from the main source.

Finally, it can be noticed when compensating procedure starts, the results in figures 10, 11, and 12 fluctuate in a short time as they are shown in the magnified portions. The DCAP through switching operations increases and decreases the voltage of capacitance till reaches the double of supply voltage that is compensating for the reduced voltage due to inductive loads. So as shown, the compensating does not occur sharply rather it is fluctuating in exponential form and is set to the optimum lower value in a very short time.

5. CONCLUSION

In this paper, the reactive power compensation in the smart home has been presented. Smart home appliances include different types of loads with major inductive loads such as water pumps, refrigerators, air conditioning systems, etc. For compensating reactive power, a modified dynamic capacitor, DCAP, was used. Different scenarios have been implemented for validating the DCAP performance. Simulation results have shown that DCAP compensated the inductive reactive power for all different cases whether home appliances receive power from the main power grid or local generator and with fixed and varied supply voltages. The best performance of DCAP in the compensation process was in reducing the load current and consequently reducing the consumption of electricity. Also, DCAP has improved the quality of electricity by keeping the power factor at unity, increasing the load voltage, and increasing the efficiency of the appliances.

Conflict of Interest

The author certifies that there is no financial conflict of interest

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