Use of Adaptive Thermal Storage System as Smart Load for Voltage Control and Demand Response

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Abstract-- This paper describes how a large-scale ice-thermal storage can be turned into a smart load for fast voltage control and demand-side management in power systems with intermittent renewable power whilst maintaining its existing function of load shaving. The possibility of modifying a conventional thermal load has been practically demonstrated in a refrigerator using power electronics technology. With the help of an electric spring, the modified thermal load can reduce power imbalance in buildings whilst providing active and reactive power compensation for the power grid. Based on practical data, a building energy model incorporating a large-scale ice-thermal storage system has been successfully used to demonstrate the advantageous demand-response features using computer simulation of both grid connected and isolated power systems. The results indicate the potential of using ice-thermal storage in tall buildings in reducing voltage and frequency fluctuations in weak power grids.

***Index Terms*— Smart loads, thermal storage, adaptive building energy modeling, electric springs**

I. Introduction

According to the World Health Organization (WHO) [1], by the middle of the 21st century, the urban population will almost double, increasing from approximately 3.4 billion in 2009 to 6.4 billion in 2050. Almost all urban population growth in the next 30 years will occur in cities of developing countries. According to [2], there are over 411 cities with population over 1 million. In Europe, buildings consume about 40% of total electricity [3]. In many large Asian cities, such as Singapore, Hong Kong and Taipei, plans have been made to install offshore wind farms. Such off wind farms will be linked to the local power grids that supply electricity to many tall buildings. In a recent real case study on the impact of offshore wind farm connection in Taiwan [4], four issues have been highlighted. They are: load flow, fault current, voltage variation and transient stability. In large Asian cities, residential, commercial and industrial buildings consume over 90% of the total electricity generated for the city. Commercial buildings alone consume 66% of total electricity and are therefore the major factor in power consumption [5] (Fig.1) in Hong Kong. Energy consumption of tall buildings can in principle be “smartly controlled” with modern Power Electronics Technology so that it can be “adaptive” to the availability of traditional and renewable power generation. If this can be achieved, new doors could be opened to utilize the smart building energy concept to interact with future power grid fed with a mixture of traditional and renewable power generation. Smart building energy usage can be a highly effective demand-response solution to meeting the objectives of enhancing power system stability and reducing energy wastage, energy storage requirements and operating costs.

Energy storage is an effective means to handle power supply and demand imbalance. However, large-scale battery storage is usually not practically viable because of cost, limited capacities and environmental issues. In tall buildings, thermal load is a considerable portion of the total electric load. It is shown in [6] that thermal loads contribute to about 45% of the total electric power consumption in buildings (Fig.1). The use of thermal energy storage in commercial buildings has been considered in China [7], Singapore [8] and Italy [9]. In [7], optimized allocation and control of storage devices according to their types and capacities has been studied with the objective of reducing costs and energy saving. Their conclusion is that the thermal storage devices and the water tanks are useful to saving energy cost in all seasons, while the electric battery is not economical due to its high investment cost and short life-time.

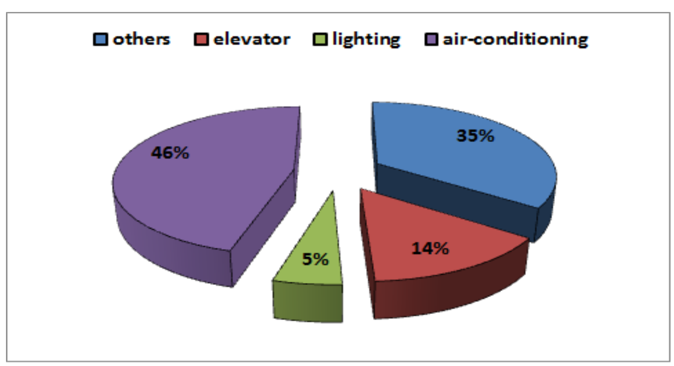

Fig.1 Typical power usage in tall buildings [5]

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Using thermal loads for demand-side management is not new. An important reference [10] has reported interesting site test results that a population of refrigerators and electric space heaters can provide frequency reserve. Water-based thermal load is considered as an attractive option of energy buffer because its cost is low when compared with that of batteries [11]. Day-ahead thermal load scheduling [12] and algorithm-based control methods for thermal loads [13]-[17] have been reported. Most of these references do not involve the electronic control aspects of the thermal loads. In addition, their focuses do not involve the technical details of achieving instantaneous demand response in real time. If large-scale thermal loads can be incorporated into building energy model (also known as building load model), then the interactions of building loads and power grid can be studied [18].

Commercial ice-thermal storage systems have been proposed as a means of reducing peak load demand as shown in Fig.2 [19]. Large-scale ice-thermal storage systems of several hundreds of kilo-Watts (e.g. >300kW) have been installed in building complexes in South East Asia for cooling a group of buildings. One advantage of using ice-thermal storage systems is to shift almost 40% of the total energy consumption to off-peak hours. On one hand, the peak load shaving effect during the daytime helps to avoid overload for the power grid. On the other hand, it reduces the cooling cost of the building by benefiting from the relatively low electricity costs during the off-peak hours in some countries.

This paper describes firstly how an ice-thermal storage can be turned into a smart load with the use of an electric spring with active and reactive power compensation capabilities [20]-[22]. Then it demonstrates that such adaptive load when embedded into a building energy system can provide extra benefits for the power grid, including instantaneous demand response for the power grid and power balancing within the building's power system. The building energy model has been incorporated into a power system fed by both traditional power generator and renewable power source of intermittent nature under both stiff and weak power grid conditions. Because the ice-thermal storage system utilizes a compressor drive like a refrigerator to produce ice, a conventional refrigerator has been practically modified into a smart refrigerator using power electronics technology. Practical results of the conventional and the smart refrigerator are included to demonstrate the proposed principle.

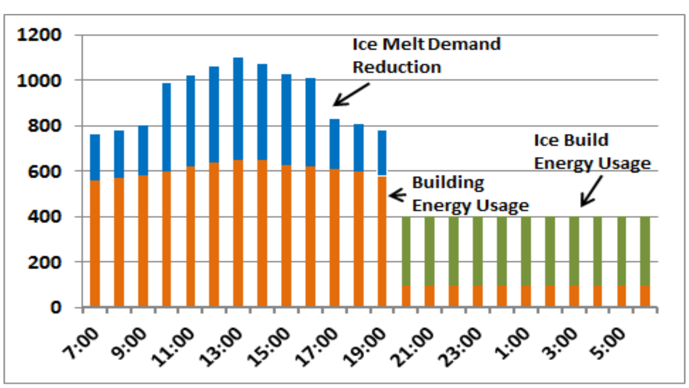


Fig.2 Electric demand profile for typical commercial building with ice-thermal storage (redrawn from [19])

II. Using Ice-Thermal Storage System as a Smart Load in Buildings

A. Turning an Ice-Thermal Storage System into an smart load adaptive to power fluctuation

From an electrical engineering point of view, an ice-thermal storage system consists of a rectifier, a power inverter fed ac motor driving a compressor. Such a system can be modified into an adaptive load as shown in Fig.3. A 3-phase electric spring (ES) with active and reactive power compensation capabilities [22] consists of power inverter with L-C filters and an active power source as shown in Fig.4. Such power source can come from an ac-dc power converter using the same 3-phase supply. The controller uses pulse-width-modulation (PWM) strategy to switch the power inverter in order to generate a PWM voltage waveform. The LC filters reduce the high-frequency harmonics. The voltage of the filter capacitor is considered as the ES output voltage which can be controlled dynamically so that the voltage across the modified ice-thermal storage system can be controlled. Since the ES is connected in series with the thermal load, its current is identical to the load current. This also means that the voltage V_o becomes the input voltage of the modified ice-thermal storage system. The front-end power factor correction (PFC) circuit ensures that the entire ice-thermal storage system behaves like an equivalent resistive load.

The load consumption is determined by a temperature-voltage (*T-V*) setting with a negative slope and a droop characteristic. If the voltage V_o is small, the temperature setting of the ice-thermal storage system is high, thereby resulting in low load consumption. On the contrary, if V_o is large, the temperature setting is low and the load consumption is large. Typical profiles of the load power and temperature setting is illustrated in Fig.5. Therefore, the power consumption of the modified ice-thermal load behaves like a resistive load, which can consume power adaptively according to the availability of power generation. Since the angle between the load current and the ES voltage can be controlled, the ES can provide active and reactive power compensation as explained in [12].

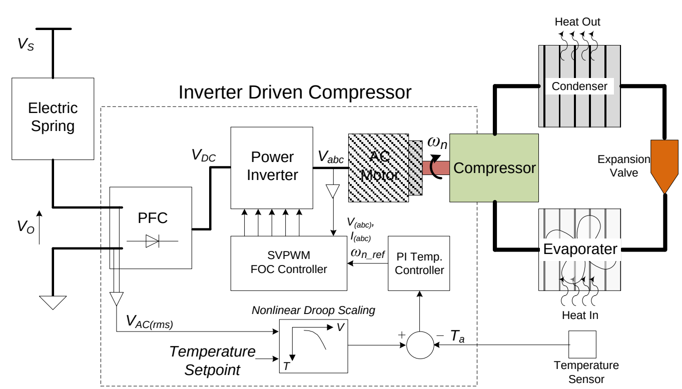


Fig. 3 Proposed control block diagram of a smart refrigerant condenser. The power consumption can vary depending on the input AC voltage.

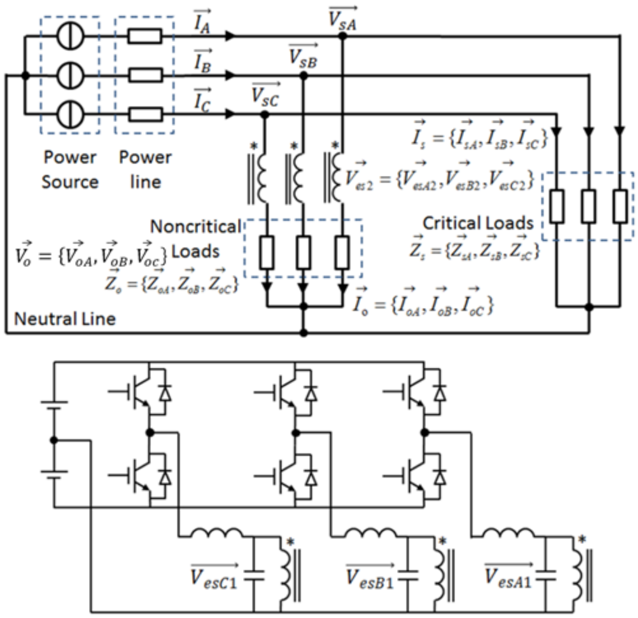


Fig.4 Circuit schematic of a three-phase electric spring with active power source [13]

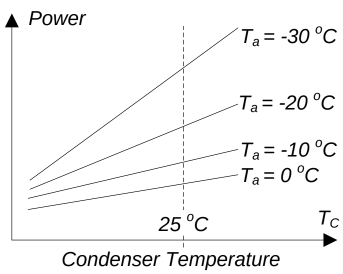


Fig. 5 Typical power consumption characteristic of a refrigerant condenser.

B. Building Energy Model

The typical power consumption profile in Fig.2 is used as the basis to form the building energy model in this study. The total electric load is divided into three parts, namely the critical load, non-critical load and the ice-thermal storage system. Critical load refers to load that requires a stable mains voltage. An example is the electric lift. Non-critical load refers to load that can tolerate some degree of mains voltage fluctuation, such as the lighting system used in the underground parking area and electric water heaters. The ice-thermal load, which is considered as a special non-critical load in this study, is connected in series with a three-phase ES as described in Fig.4.

Based on the building energy consumption profile in Fig.2, the power profile can be divided into two portions, namely the office-hour period (from 7am-10pm) and non-office hour period (10pm-7am). The building loads are classified into 3 groups, namely the critical load, the non-critical load and the adaptive ice-thermal load. As shown in Fig.6, the non-critical load and the ice-thermal load are associated with ES.

From 7am-10pm, the ice-thermal storage system does not consume power. The fan cooling system blows cool air (from the melting ice) into the building. Such power consumption is considered as part of the non-critical load in the building. From Fig.2, the power consumption of the building load varies within the range from 550 kW to 650 kW hourly. During this period, the three phase load in this building is assumed to be unbalanced with the power ratio between phase A, phase B and phase C being 0.4:0.33:0.27. The ratio of the critical and non-critical load during the office hours is assumed to be 70:30 because the ice-thermal storage load (which is a sizeable non-critical load) has been shifted to the non-office hour period.

From 10pm-7am, the adaptive ice-thermal storage system consumes power to produce ice. Under steady-state conditions, its power rating is 300kW. Other critical load in the building is assumed to be 100kW (Fig.2). Therefore, the ratio of the critical load and non-critical load is assumed to be 10:30 in the non-office hour period.

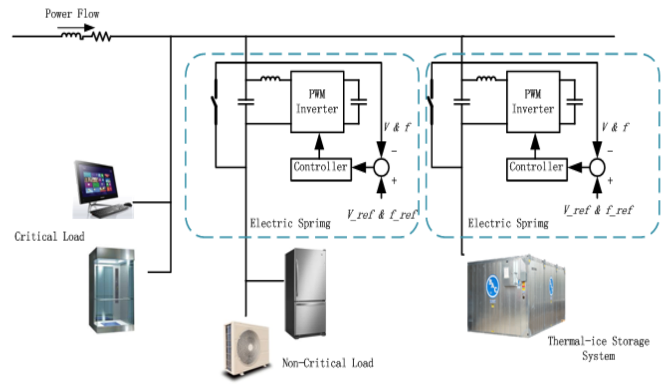


Fig.6 Schematic of a building energy model comprising critical load, non-critical load (associated with an ES) and the ice-thermal storage system (associated with an ES)

III. Stiff and Weak Power Grid with Intermittent Renewable Power Source

A. Stiff Power Grid

In this study, two situations are considered. The first situation is called the city mode operation. It assumes a stiff power grid that is powered by the feeder of a traditional power station (with a stable mains frequency) and an intermittent renewable power source (such as an offshore wind farm), which is 20 km away from the building with the ice-thermal storage load. A schematic of such power grid is shown in Fig.7. To match the level of power consumption of the building model, a small offshore wind turbine (such as NTK 300) is adopted in the simulation studies.

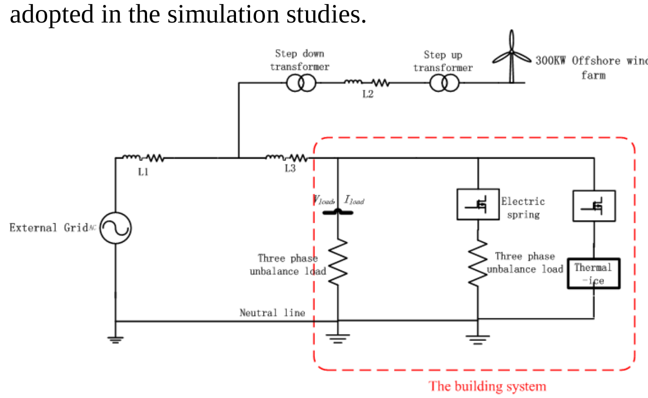


Fig.7 Schematic of a building energy model fed by a stiff power grid and a wind generator

Table I. Parameters of the stiff power grid under consideration

External Grid		
frequency	Apparent power	Terminal voltage

50 Hz		456 V
Offshore wind turbine		
Apparent power	Terminal voltage	
300 kW	400 V	
Step down Transformer		
Configuration	Apparent power	Winding Impedance
33 kV/420 V, Delta/Star	0.5 MVA	0.06+j0.12 p.u.
Step up Transformer		
Configuration	Apparent power	Winding Imdedance
400 V/33 kV, Delta/Star	0.5 MVA	0.06+j0.12 p.u.
Distribution line		
Impedance per kilometer (*R*+*JX*)		0.11 + j0.39
L1	L2	L3
0.2 km	20 km	0.1 km

B. Weak Power Grid

The second scenario under consideration is related to a weak power grid in which the dynamics of the local generator (i.e. frequency stability) is significant. An example is a hotel building complex in an offshore island. In such a typical microgrid, it is assumed that electricity is supplied by a local power generator and a nearby renewable power source as shown in Fig.8. In this study, the wind generator is assumed to be 2 km away from the building. The parameters of such weak power grid with renewable power source are given in Table II. The schematic of the local generation with governor control is shown in Fig.9(a). The control parameters of a simplified model are provided in Fig.9(b).

Table II. Parameters of the weak power grid under consideration

Steam turbine synchronous generator		
frequency	Apparent power	Terminal voltage
50 Hz	1.5 MVA	10 kV
Offshore wind turbine		
Apparent power	Terminal voltage	
300 kW	400 V	
Transformer		
Configuration	Apparent power	Winding Impedance
10 kV/420 V, Delta/Star	1.5 MVA	0.06+j0.12 p.u.
Distribution line		
Impedance per kilometer (*R*+*JX*)		0.11 + j0.39
L1	L2	L3
0.2 km	2 km	0.1 km

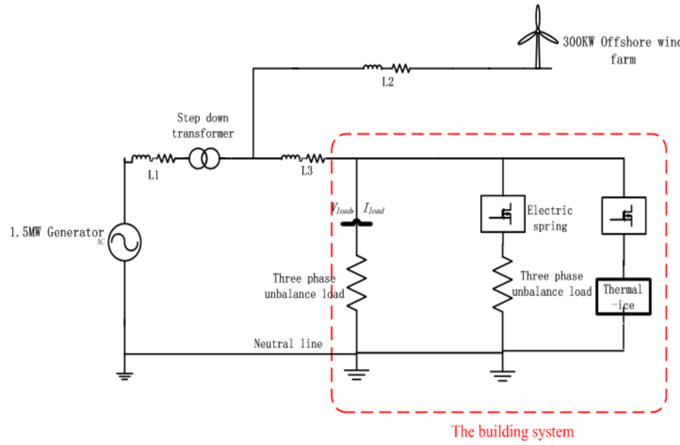


Fig.8 Schematic of a building energy model fed by a weak power grid and a wind generator

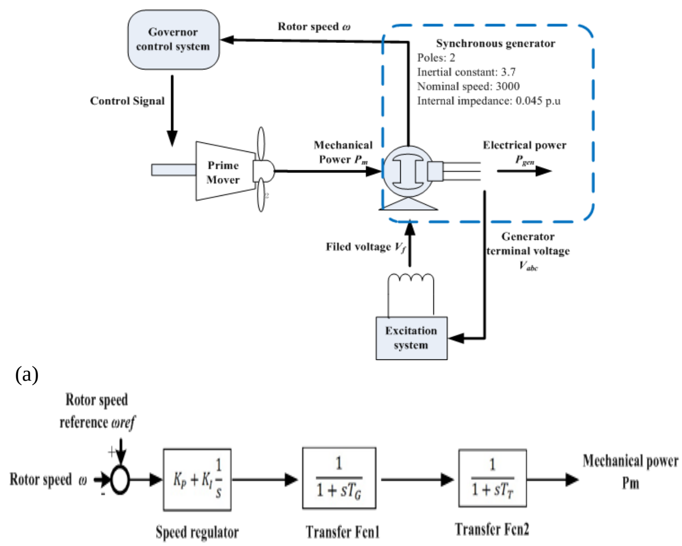


Fig.9 Block diagram of an electric generator. (b) A simplified speed control scheme for the prime mover for the generator

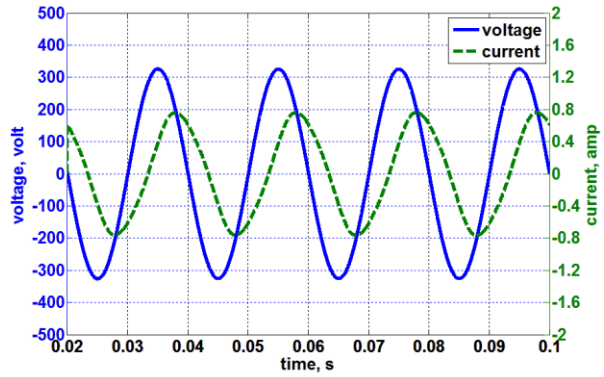
IV. PRACTICAL EVALUATION OF SMART THERMAL LOAD

A. Practical tests on a standard and a modified refrigerator

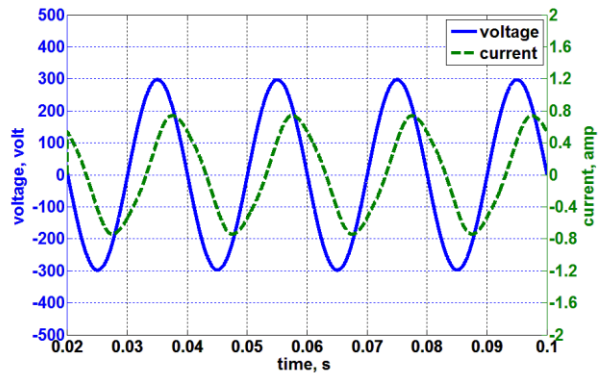
The concept of using power electronics technology to alter existing thermal load as smart load for compatibility with the operation of the ES is practically demonstrated with a refrigerator. The characteristic of a standard refrigerator and that of a modified refrigerator are first captured and then used for comparison. The modification of such refrigerator is based on the block diagram in Fig.3.

(1) Practical results of a standard refrigerator

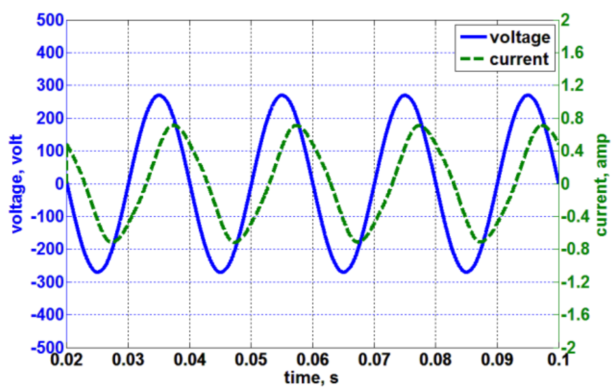
In this test on the standard refrigerator, a variable ac voltage is applied to the refrigerator. The measured input voltage and current waveforms at the input voltage of 230V, 210V and 190V are included in Fig.10. It is noted that the characteristic of the standard refrigerator is not resistive. The first reason is that the power factor is not close to 1. Because the refrigerator does not have any power factor correction circuit, the power factor falls within a typical range of 0.55 to 0.6. The second reason is that the V-I characteristic is not linear.



(a) Input Voltage = 230V



(b) Input Voltage = 210V



(c) Input Voltage = 190V

Fig.10 Measured input voltage and current of a standard refrigerator

(2) Practical results of a modified refrigerator

A simplified control scheme has been implemented in a modified refrigerator as shown in Fig. 11. A power factor correction circuit is used to feed a power inverter module for driving the refrigerator in order to ensure that the input current of the modified refrigerator is a sinusoidal waveform and in phase with the input voltage. In the test, a variable voltage source is used to control the input voltage of the modified system. (This voltage will be supplied by the output of the ES.) This variable voltage source simulates the output voltage of the ES. As the voltage applied across the input of the PFC circuit is varied, the output frequency of the inverter is altered in a manner that the input current of the PFC circuit varies linearly with the input voltage, thus forming a resistive behavior for the entire modified refrigerator. Table III shows the nonlinear mapping of the input voltage and the inverter's output frequency for driving the compressor motor.

The measured input voltage and current waveforms of this modified refrigerator system are shown in Figs.12 (a), (b) and (c) for the input voltage of 230V, 210V and 190V, respectively. It can be seen that the PFC circuit has been effective is shaping the input current to be in phase with the input voltage and the current waveform is close to the sinusoidal one. The input current of the modified refrigerator is proportional to the input voltage as shown in Fig.12. It should be noted that the mapping in Table III is for steady-state situation. In a dynamic situation, one should expect some delay for the non-critical load power to reach the targeted power due to the mechanical time constant of the rotor in the drive system.

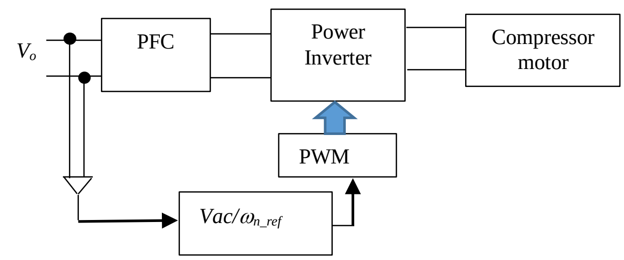
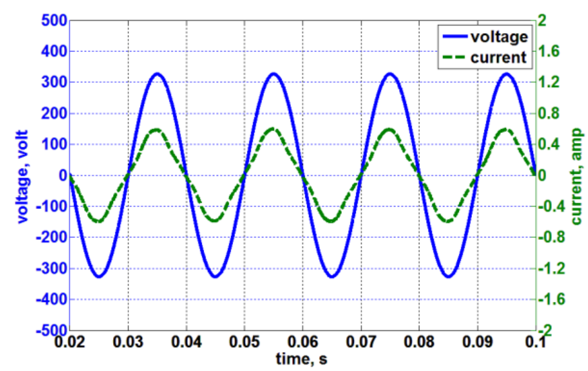


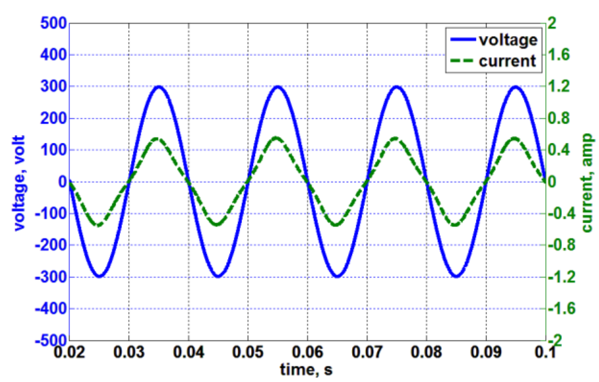
Fig. 11 A simplified control scheme of a modified refrigerator

TABLE III NONLEAR MAPPING OF THE INPUT VOLTAGE AND INVERTER FREQUENCY OF THE SMART REFRIGERATOR

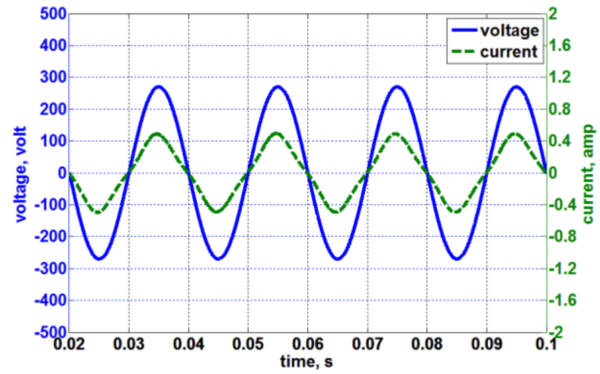
Input voltage *Vac* (V)	Input Current *Is* (A)	Inverter Output Frequency (Hz)
230	0.420	50
220	0.408	45.1
210	0.383	42
200	0.368	37.7
190	0.345	30.2



(a) Input Voltage = 230V



(b) Input Voltage = 210V



(c) Input Voltage = 190V

Fig.12 Measured input voltage and current of a smart refrigerator

(3) Comparison of original and modified characteristics of the thermal load

The variations of the input voltage and the input current of the standard refrigerator and the modified one have been measured and plotted together in Fig.13. Several important observations can be made:

- The original V-I characteristic is not resistive. Firstly, there is obvious angular displacement between the input voltage and current as shown in Fig.10. Secondly, the V-I curve is not a linear one as shown in Fig.13.
- The modified V-I characteristic is a linear curve (Fig.13). This means that the input current of the modified load is proportional to the input voltage. Since the input current is in phase with the input voltage and it has a near sinusoidal shape, the overall modified load exhibits a resistive characteristic.
- The input current of the smart refrigerator is smaller than that of a conventional one because the smart refrigerator has a power factor close to 1.0 whilst the conventional one has a power factor around 0.55 to 0.6.

These practical results confirm the idea that a conventional thermal load can be converted as a load with resistive characteristic through the use of power electronics technology. It should also be noted that some modern refrigerators and air-conditioners (such as those produced by Hitachi) have already incorporated the power factor correction unit and power inverter for power control purposes. Therefore, such systems can be easily modified into the form described in Fig.3 without increasing costs to the systems substantially.

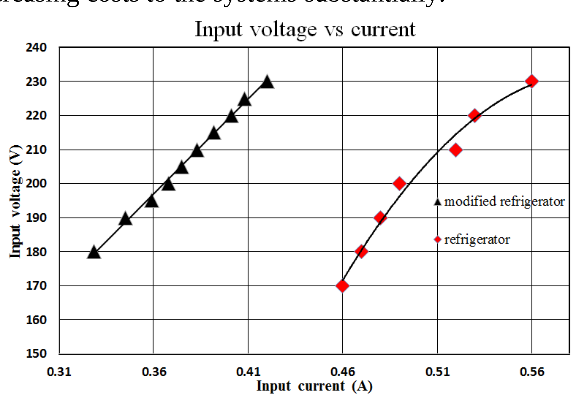


Fig. 13 The characteristics of the original refrigerator and the modified refrigerator system

A programmable power supply has been used to emulate the power system with intermittent power sources in Fig.8 for testing the modified thermal load. The line impedance consists of a resistor of 0.3Ω and an inductor of 3.6mH. The modified refrigerator has been tested with and without the activation of the ES. Fig.14 shows the mains voltage waveforms at the end of the distribution line with and without activating the ES. Before activating the ES, the mains voltage is below the nominal value of 240V. It can be seen that the modified thermal load can reduce the mains voltage fluctuation and keep the voltage close to the 240V level. Fig.15 shows that the ES allows the non-critical load voltage to fluctuate so that the power consumption of the modified thermal load can fluctuate to absorb the power fluctuation in the power generation.

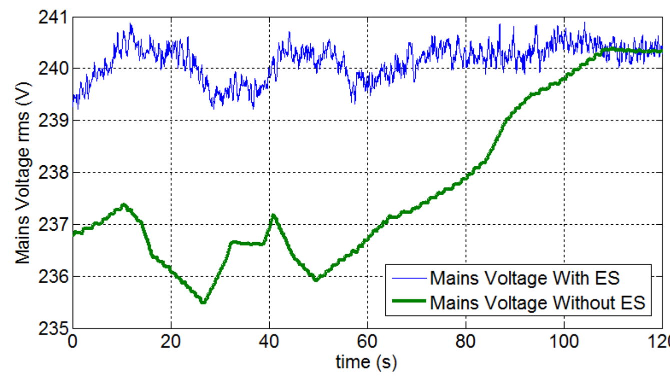


Fig.14 Measured mains voltage with and without the use of the ES

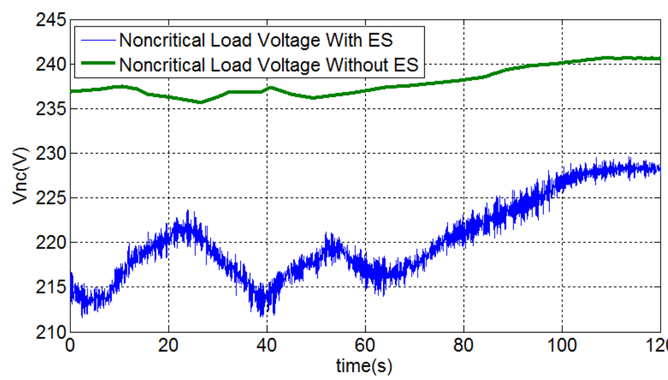


Fig.15 Measured voltage across the non-critical load with and without activating the ES

V. PERFORMANCE EVALUATION OF THE MODIFIED ICE-THERMAL STORAGE SYSTEM IN POWER SYSTEM SIMULATION

In order to evaluate the performance of the smart ice-thermal load under short and long time frames, two sets of simulations in the time frames of minutes and hours have been conducted for each case. The ES plays the roles of reducing mains voltage fluctuation, maintaining power balance of supply and demand and also reducing power imbalance in the 3-phase power systems. Fig.16 shows a typical wind profile used in the following simulation studies for the short-time frame (i.e. simulation studies by minutes).

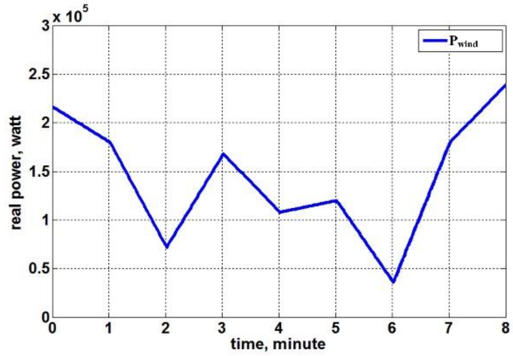


Fig.16 Typical wind power profile used in the simulation studies for short time frame

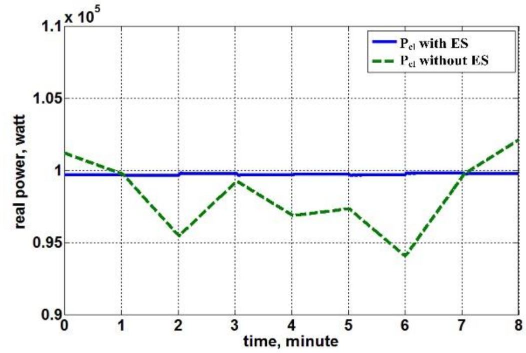


Fig.18 Profiles of the critical load power consumption (P_{cl}) with and without using ES

A. Stiff Power Grid

(i) Simulation study by minutes

The information of the stiff power grid is provided in Table I. Under the effect of the wind profile in Fig.16, simulations have been conducted to evaluate the performance of the ice-thermal storage system with and without the ES. The simulated results with and without using ES are plotted together for easy comparison.

The fluctuating wind power generation in Fig.16 affects the mains voltage as shown in Fig.17 which displays the mains voltage (which is also the voltage across the critical load) with and without using ES. Observation of the intermittent wind profile in Fig.16 and the mains voltage profile (green curve in Fig.17) shows that the two profiles have the same pattern. Without ES, the intermittent wind power disturbs the mains voltage, resulting in the voltage deviating slightly (due to stiffness of the system) from its nominal value of 240V. The ES has been shown to be effective in regulating the mains voltage close to its nominal value.

Fig.18 shows the critical load power consumption profiles with and without using ES. Without ES, the fluctuating mains voltage leads to fluctuating critical load power because the critical load is modeled as a resistive load. With the use of ES, the voltage fluctuation is reduced. Consequently, the critical load power is stabilized with the help of using ES as shown in Fig.18.

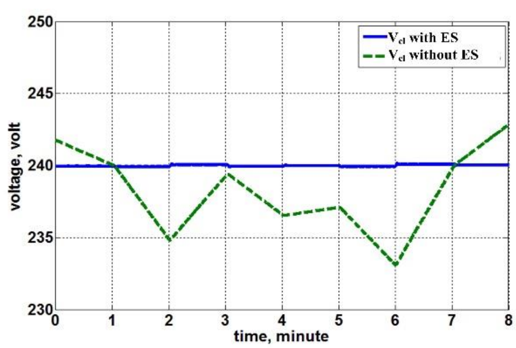


Fig.17 Profiles of the mains votlage across the critical load (V_{cl}), with and without using ES

The ES reduces the mains voltage fluctuation by providing reactive power compensation as shown in Fig. 19. Note that the reactive power compensation profile in Fig. 19 follows the intermittent wind profile in Fig. 16. This indicates that the ES reacts in real time to deal with voltage fluctuation by providing reactive power compensation in order to regulate the mains voltage to its nominal value. Simultaneously, the ES allows the voltage across the non-critical load to fluctuate with the wind power profile as shown by the blue curve in Fig. 20. Consequently, the non-critical load power consumption is automatically modulated to balance power supply and demand. Because of the stiffness of the power grid, the ES does not need much active power for the voltage regulation as shown in Fig. 21. The ES essentially provides reactive power compensation in a stiff power grid as shown in Fig. 19. (It will be seen that the active power compensation provided by the ES will be significant in a weak power grid.)

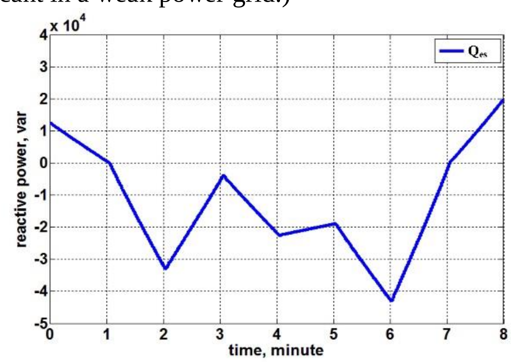


Fig.19 Reactive power compensation (Q_{es}) by ES

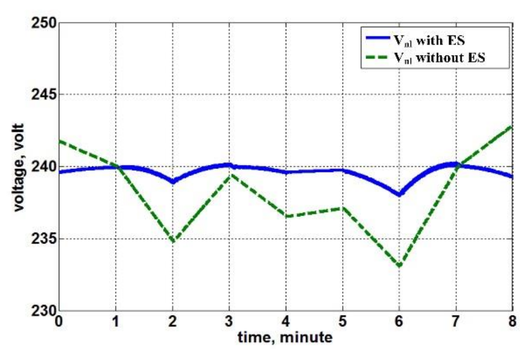


Fig.20 Profiles of the votlage across the non-critical load (V_{nl}) with and without using ES

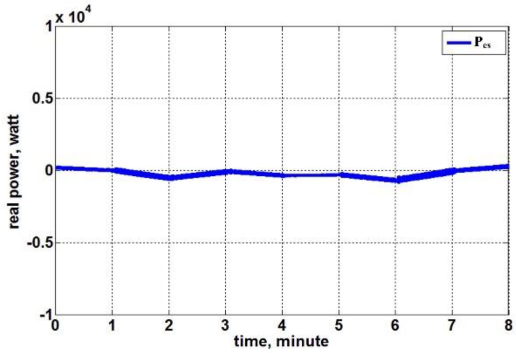


Fig.21 Variation of the active power in the ES

(ii) Simulation study by hours

One of the main functions of the ice-thermal storage system to provide peak load shaving. In the presence of substantial amount of intermittent renewable power generation, the situation of the power consumption profile of the building is slightly different from the ideal case shown in Fig.2. As shown in Fig. 22, the intermittent wind power causes power fluctuation (appearing as ripples) in the power profiles. As expected, the use of the ice-thermal storage system can reduce the peak load of the building. In addition, with the ES of the ice-thermal storage activated during the non-office hours, the power ripple can be substantially reduced. The provision of a fair amount of load consumption by the ice-thermal storage system allows the generator of the power plant to continue to operate at night, thereby avoiding the cost and inconvenience of shutting down and re-starting the generator during this period.

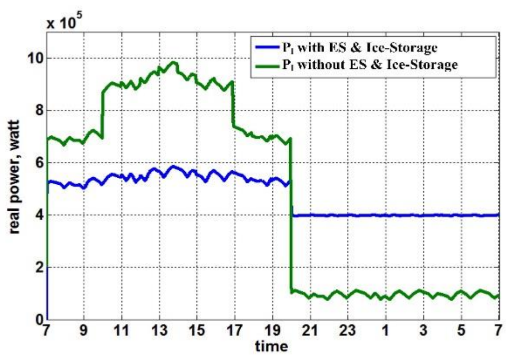


Fig.22 Profiles of the total power consumption (P_l) with and without using ES and the ice-thermal storage system

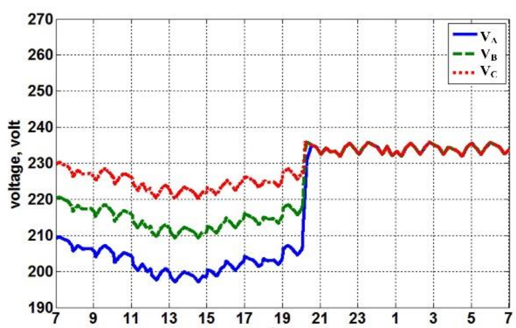


Fig.23 Profiles of the three-phase voltage over a 24h period without ES

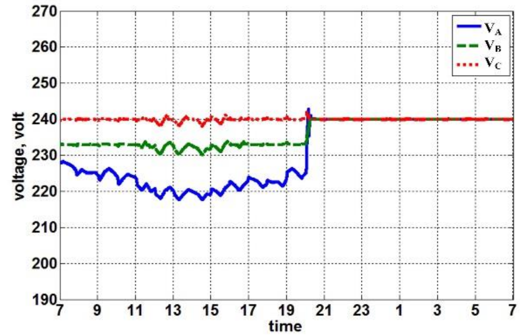


Fig.24 Profiles of the three-phase voltage over a 24h period with ES

Because the critical and non-critical loads of the building model are assumed to be imbalanced, it is interesting to observe the power imbalance of the 3-phase power system. Fig.23 shows the three phase voltages over a 24h period when the ES is not activated. Two observations can be made. Firstly, the intermittent nature of the wind power generation causes ripple in the phase voltage profiles. Secondly, from 7am to 10pm, the three phase voltages are not balanced. One phase voltage drops below 200V momentarily for a nominal mains of 240V. The corresponding results with the use of ES are recorded in Fig.24, which shows that the power imbalance and voltage ripples are reduced. The minimum phase voltage of the most heavily loaded phase is pushed up almost by 20V when compared with that in Fig.23. After 10pm when the majority of the daytime loads are removed, the ice-thermal storage system which is assumed to be a balanced three-phase load does not cause power imbalance. From these simulation studies, it can be seen that the ice-thermal storage system, when worked with an ES, can reduce voltage fluctuation in the mains voltage by providing dynamic reactive power compensation and simultaneously reducing power imbalance within the power system within the building in a stiff power grid.

B. Weak Power Grid

(i) Simulation study by minutes

For a micro (weak) grid with relatively small rotor inertia in the generator, the rotor dynamics and hence frequency stability become major issues. For frequency stability, it is essential that the power demand follows the power generation. Since intermittent power generation is involved, the use of smart load adaptive to power generation such as the proposed adaptive ice-thermal storage system forms a demand response solution.

For the short time frame study, the same wind power profile of Fig.16 is adopted. Emphasis is placed on the effects of the intermittent wind power on the frequency variation of the small power generator in a micro (weak) power grid. Fig.25 shows the power profiles of the relatively small generator with and without ES. It is noted that the power variation is much reduced when ES is activated. The reason for this can be explained from the observation of the non-critical load voltage shown in Fig.26, in which such voltage is allowed to fluctuate with the wind power profile in Fig.16. The non-critical load power consumption profile follows the wind power profile (see blue curve in Fig.26). That is, when the wind power drops the non-critical load voltage drops too, leading to the corresponding reduction in non-critical load power consumption as shown in

Fig.27. One key function of the ES is to ensure that the non-critical load profile follows that of the intermittent wind power profile. This is an effective approach to enforce the new control paradigm of power demand following power supply [20]. In practice, the power balance between supply and demand may not be achieved solely by the variation of the non-critical load power consumption. The ES also plays a part in reducing the imbalance between power supply and demand.

Fig.28 shows the variation of the active power in the ES. Note that the active power profile provided by the ES in Fig.28 is just opposite to the wind power profile in Fig.16. It can be seen that the ES also plays a part in active power compensation, although the amount of active power is much smaller than that in the non-critical load in Fig.28. The combined variation of this non-critical load power and the active power in the ES according to the profile of the renewable power therefore reduces the power imbalance between the power supply and demand. This feature is also reflected in the reduced fluctuation in the power supplied by the small generator in Fig.25. Consequently, the frequency fluctuation of this weak grid is much reduced when the ES is in use as shown in Fig.29.

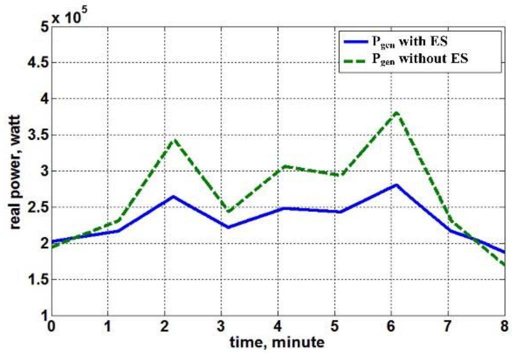


Fig.25 Profiles of the real power supplied by the relatively small generator (P_{gen}) with and without ES

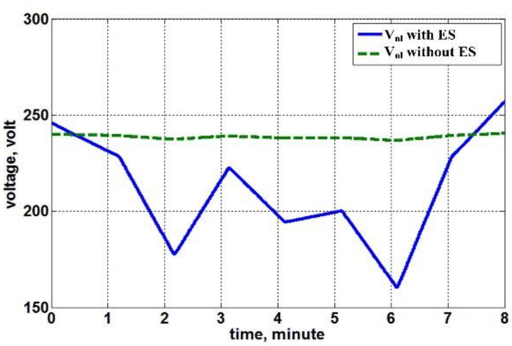


Fig.26 Profiles of the non-critical load voltage (V_{nl}) with and without ES

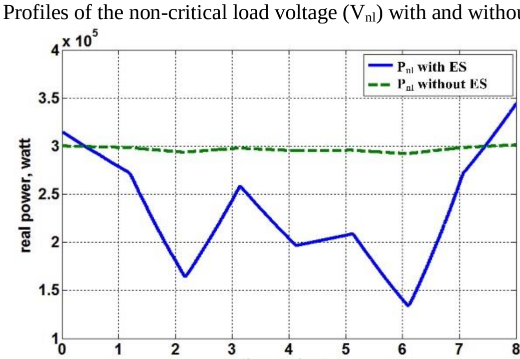


Fig.27 Profiles of the non-critical load power (P_{nl}) with and without ES

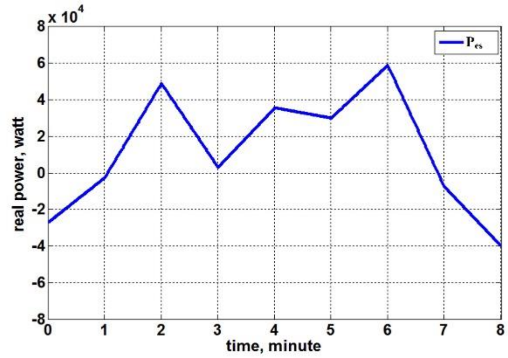


Fig.28 Profile of the active power variation in the ES

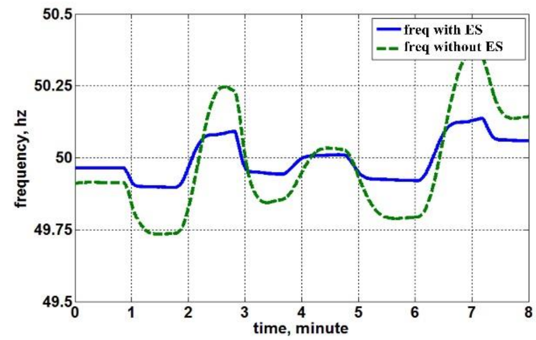


Fig.29 Profiles of the mains frequency with and without ES

(ii) Simulation study by hours

Similar to the study on the stiff power grid, simulation tests have been conducted on the hourly basis. Fig.30 shows the profiles of the total power consumption in the building over 24h with and without using the ES and the ice-thermal storage system. Again, the simulation results show that the ice-thermal load can provide peak power shaving function while the ES can reduce the power ripple caused by the intermittent nature of the wind power. The profiles of the three phase voltages without ES are shown in Fig.31. From 7am to 10pm, the unbalanced loads cause obvious phase imbalance. When such unbalanced loads are turned off at 10pm, the system becomes essentially balanced because the ice-thermal storage system is considered as a balanced load. Finally, the corresponding profiles of the phase voltages with the use of ES are included in Fig.32. Again, it can be observed that the power system imbalance is reduced from 7am to 10pm.

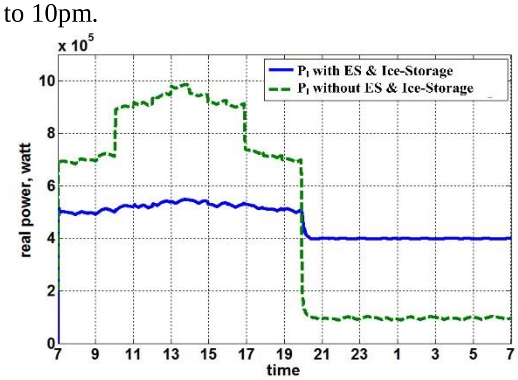


Fig.30 Profiles of the total power consmption of the building with and without using ES and the ice-thermal storage system.

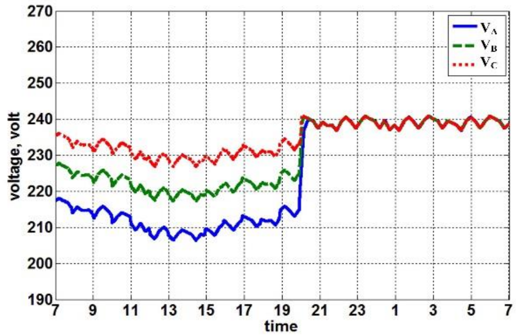


Fig.31 Profiles of the phase voltages without ES

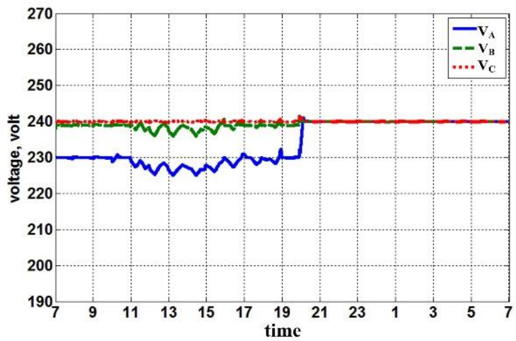


Fig.32 Profiles of the phase voltages with ES

C General Discussion

The practical and simulation results presented here indicate that conventional thermal loads can in principle be converted into smart loads that are adaptive to the availability of power generation. The ES is based on a power inverter which can be PWM-switched at 100kHz. Typically, the LC filter (used for deriving the sinusoidal voltage of the ES voltage output) has a bandwidth of 10% of the switching frequency. Thus, the LC low-pass filter has a bandwidth of 10kHz. In other words, the ES can react within 0.1 ms. Compared with other day-ahead or hour-ahead demand-response solutions, the ES can be considered as offering almost instantaneous demand response. Its use with large-scale thermal loads in tall buildings would offer an indoor solution to reduce fluctuations of voltage and frequency of the power grid, power imbalance and peak power demand. Together with outdoor solutions such as smart LED street lighting systems [23], large-scale smart thermal loads with ES embedded could form a distributed demand response for future power grids.

VI. CONCLUSIONS

This paper demonstrates the concept of smart buildings that incorporate large-scale adaptive thermal loads as a demand response solution to future power grid with substantial penetration of intermittent renewable energy sources. It has been shown that conventional thermal load can be made adaptive with the use of an electric spring. For the first time, a conventional refrigerator has been practically modified for operation with an electric spring in order to confirm the feasibility of using ice-thermal storage system as an adaptive load. Based on government data on electric loads for buildings, a building energy model incorporating a three-phase electric spring with a modified ice-thermal storage system has been developed for simulation studies in stiff grid and weak grid environments. Such building energy model has the uniqueness of being adaptive to the power system and can dynamically respond to changes of power generation. The results indicate that, while the traditional peak load shaving function is retained, the adaptive ice-thermal storage system can reduce the mains voltage fluctuations and voltage imbalance in the power grid. The adaptive thermal load can also reduce frequency fluctuations in a weak power grid. For mega cities with plans to install offshore wind farms (e.g. Singapore and Hong Kong) buildings with the installation of adaptive ice-thermal storage systems have the potential to form a stabilizing force for the power grid in the presence of intermittent renewable power generation. The adaptive building energy model in this paper will facilitate future power system studies of the use of distributed electric springs in large power grids. It provides a link between smart grid and green building research.

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