Development of a Smart Thermostat Controller for Direct Load Control Based Demand Response Applications

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***Abstract*— The demand side, which was formerly considered as an inelastic part of the power system operation, has recently been evaluated as a source of flexibility to enhance the effectiveness and economy of power system operation. Several real world examples and literature studies exist to evaluate the contribution of demand side flexibility in power system operation in this manner. Accordingly, in this study, a smart thermostat controller for direct load control based demand response applications for controlling the thermostatically controllable loads by Thermostat Set-point Control Mechanism (TSCM) method is developed differently from the existing studies, where few of them have considered the real world applicability requirements of such concepts. The concept has been experimentally verified under different case studies.**

***Index Terms*— demand response, direct load control, smart thermostat controller, thermostatically controllable appliances**

I. Introduction

A. Motivation and Background

The ever-increasing demand for electric energy and the variability of the power demand seasonally, daily or even hourly have posed challenges for electric power system operation and planning from a system operator point of view. In addition, the increasing investments on non-dispatchable renewable energy resources based power plants due to several environmental and political reasons have also a nonnegligible contribution to the mentioned power system operation complexity to continuously ensure a perfect match between power demand and supply while sustaining the economy of energy delivery.

Therefore, the power system flexibility has become a far more important issue for the effective and economic operation of power systems [1-3].

The power system flexibility is the ability of the power system to respond to the changes in demand and supply. The conventional power plants were and still are a resource of flexibility in power systems.

In this manner, in order to increase the options to provide more economic and effective solutions, energy storage systems from a single end-user scale to grid scale have also found an increasing level of implementation and research [4]. However, one of the most promising solutions in this regard is proposed as energizing the demand side, which was considered as totally inflexible from a system operator point of view until the last decades [5,6].

The demand side flexibility has been considered more widely under the concept of demand side management and more specifically demand response in the smart grid context recently [7].

The responsiveness of the demand side can be realized via different concepts; however, these concepts are generally categorized as indirect and direct load control based demand response programs. The indirect load control based demand response concept is based on applying different pricing schemes to influence the end-users' behaviors to reduce the demand in peak periods (which generally reflect the relatively higher price periods) and shift more demand to off-peak periods. However, the effectiveness of the indirect load control concept mainly relies on the rationality of the end-users, which is a stochastic issue considered as the main topic of many literature examples. Therefore, direct load control based demand response concept has found a wider area of implementation in recent periods [8].

B. Literature Review

There are several studies in the literature on the implementation of direct load control based demand response programs. These studies generally consider the remote control of a specific end-user load by the system operator, and thermostatically controllable appliances such as air conditioners, water heaters, and refrigerators come into prominence in this manner as they have an impact on the end-users' comfort with a nonnegligible time delay.

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Among the existing examples, Refs. [9-16] considered the applicability of air conditioners in the direct load control programs in this respect. The air conditioners lead to high peak demand in different regions of the world especially during the noon periods of hot summer days, and therefore have great potential to contribute to the demand side flexibility. On the other hand, many studies considered water heaters [17-19] and refrigerators [20] based flexibility potential of demand side and provided managing concepts leading to a more effective operation possibility for the system operator. A detailed literature survey in this regard can be found in Refs. [21,22] and a very detailed presentation of practical evidence in this manner can be found in Ref. [23], which are among previous studies of the Authors in this exact area of using demand side flexibility via direct load control concept for the system operation. Even the mentioned studies here and numerous huge amount of studies that cannot be referred to all here have provided seminal contributions to the literature, a very few of them focused on the implementation requirements of these operational concepts.

C. *Contributions and Paper Organization*

In this study, a smart thermostat controller for direct load control based demand response applications for controlling the thermostatically controllable loads is proposed. Two concepts can be implemented in this manner: Direct Compressor Controller Mechanism (DCCM) which enables the direct manipulation of the load by turning it on or off, and Thermostat Set-point Control Mechanism (TSCM) method which indirectly turns the load on or off considering the manipulation of the thermostat temperature set points remotely by the system operator. Here in this study, a TSCM method based concept is considered as this method has been found to be more applicable by different existing studies and the implementation of the concept is experimentally verified. The main contributions of this study are as follows:

- The study focuses on the implementation requirements of direct load control concept rather than a theoretical evaluation of the system operator point of view that can partially show the pathways of the practical implementation details for the system operators.
- The proposed structure is experimentally evaluated under real world conditions in different case studies.

The rest of the paper is organized as follows. The overview of the proposed concept is detailed in Section II. Afterward, Section III clarifies the experimental case studies regarding the implementation of the proposed concept. Finally, Section IV highlights the important conclusions of the study.

II. Overview of the Proposed Concept

The application of direct load control based demand response programs has different requirements from implementation point of view.

The use of the latest technology via smartphone applications, different communication channels, and effective system operator decision-making infrastructures play a vital role in this fashion. The general concept in this regard for a sample application of a direct load control based demand response application is visualized in Fig. 1 [24]. The smartphone application and system operator decision making methodology was recently provided in a former study of the Authors [24]. This study is an extended version of the mentioned study by focusing more on sample hardware requirements in this manner. Therefore as mentioned above, this study deals with the development of an end-user product for the realization of air conditioners oriented direct load control based demand response programs. For the control of the air conditioner load of the residential end-user via the system operator, an experimental test bed is prepared to gather the thermostat set-point data and accordingly control the air conditioner thermostatically via these data. The circuit is initially realized for pre-analysis on a breadboard as depicted in Fig. 2.

The mentioned circuit includes an infrared transmitter. The circuit protocols are designed to be fully compatible with all the different air conditioner brands. The pre-analyses of the designed circuit are conducted via an air conditioner unit existing in Yildiz Technical University Electrical Engineering Department Renewable Energy Systems Laboratory. The obtained pre-results demonstrate that the pre-design circuit can handle the required transactions successfully and then the prepared final design in printed circuit form is demonstrated in Fig. 3. Herein, the mentioned equipment is based on a microprocessor and a temperature-humidity sensor. As the equipment is connected to home area network, it can reach the server via the WebSocket protocol and periodically sends the reference temperature value, air conditioner mode, and temperature and humidity data to the server. These data can also be stored for other research purposes. Besides, the end-users can also control their air conditioner over Internet via a mobile application.

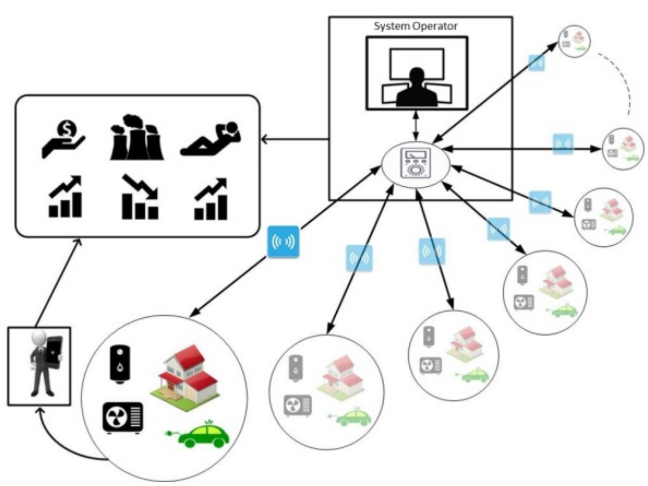

Fig. 1. A general sample concept for the implementation of direct load control based demand response strategies.

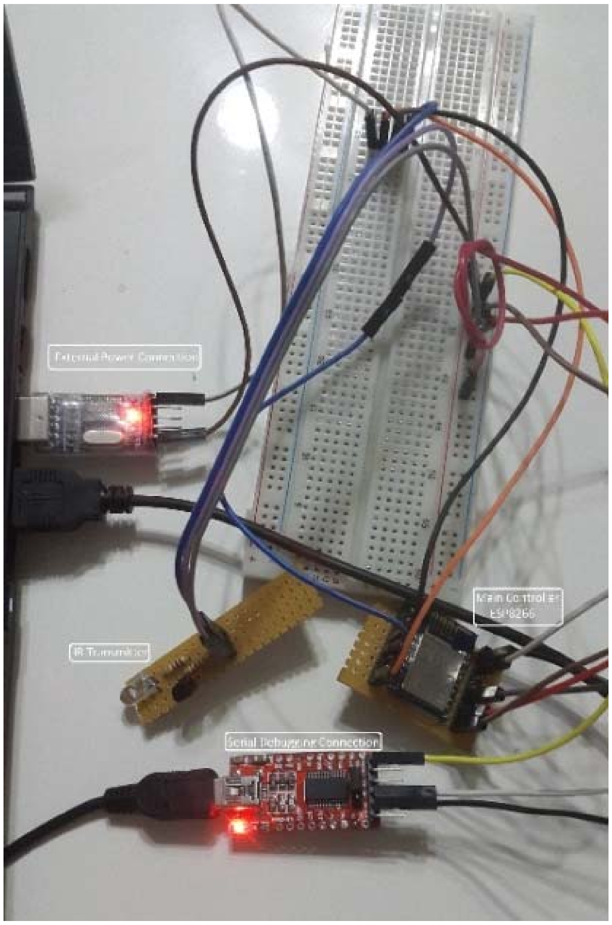

Fig. 2. The demonstration of the pre-design circuit on a breadboard.

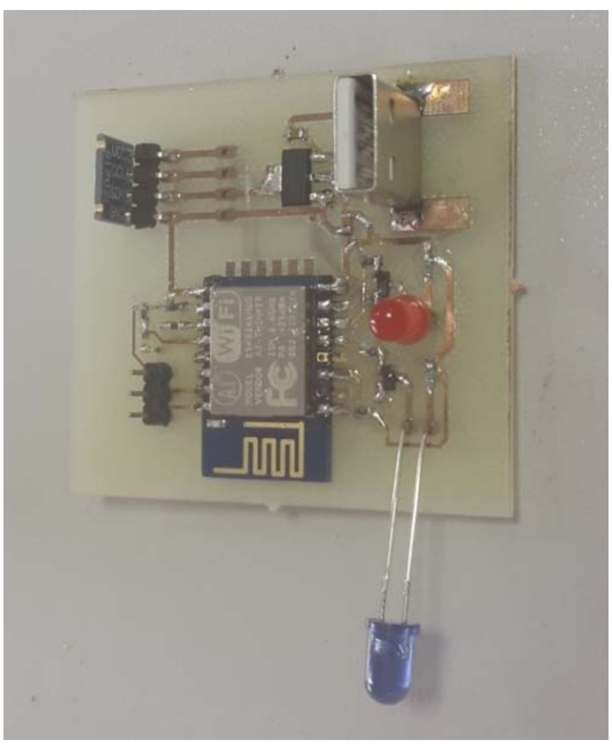

Fig. 3. The demonstration of the final circuit in printed circuit form.

The equipment checks the wireless network and sensor status during operation. If a predefined network does not exist, the equipment waits in standby mode until connecting to a pre-configured network. On the other hand, the equipment automatically shuts down if a sensor fault exists.

After the initialization process, the equipment connects to the server via the WebSocket protocol as aforementioned before and defines itself via a single ID when the socket connection is realized. The mobile application realizes the same WebSocket connection and defines the user with a single ID in order to permit the control of the defined equipment. The mobile application does not directly control the equipment, and the server manages all the communication and data packages. In this respect, the equipment and system flowcharts are shown in Fig. 4 and Fig. 5, respectively.

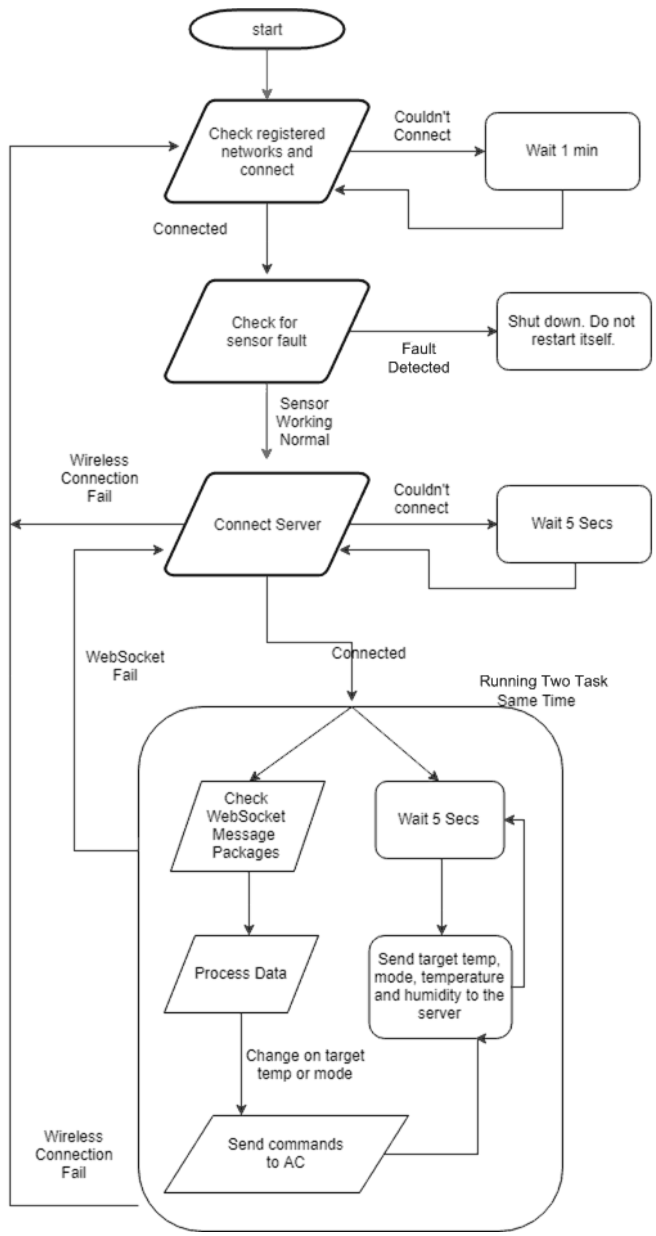

Fig. 4. The equipment flowchart.

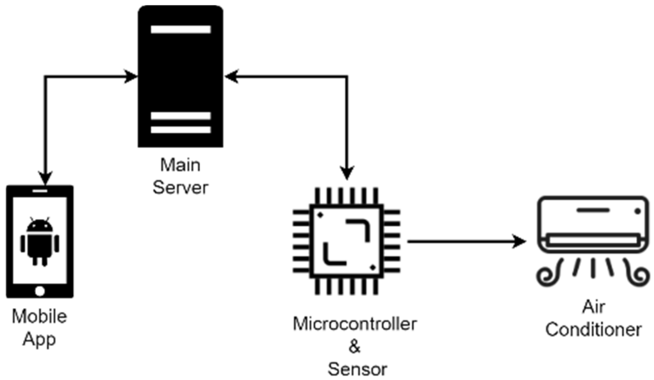

Fig. 4. The system flowchart.

III. Case Study

In order to experimentally test the circuit that controls the air conditioner considering the air conditioner temperature set points defined by the system operator for three different days as input via the external communication from TSCM point of view, an air conditioner with the specifications given in Table I is considered. The experimentally measured different conditions regarding the mentioned test days are presented in Table II.

In this manner, the results obtained for Day-1, Day-2 and Day-3 are presented in Figs. 6-7, Figs. 8-9 and Figs. 10-11, respectively. It should here be noted that the target temperature set points are changed via remote manipulation to the developed end-user equipment by the system operator interface mentioned above and also explained in detail in a previous study of the Authors in Ref. [24]. In this current study, the aim is to observe how the air conditioner operating mode accordingly changes and the ambient meteorological data and air conditioner power variations are depicted separately for each day.

TABLE I. The Specifications of the Air Conditioner Used for the System Tests

Air conditioner power [W]		
Full load	**Only fan**	**Idle**
5250	350	0

TABLE II. Different Conditions for the Test Days

Condition	Day-1	Day-2	Day-3
Ambient temperature	22°C	18°C	17°C
Ambient relative humidity	78%	56%	68%
The frequency of door and windows usage	Frequent	Rare	None

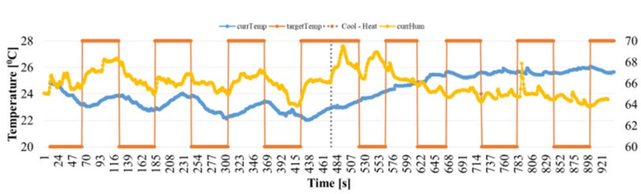

Fig. 6. The ambient meteorological conditions during the tests for Day-1.

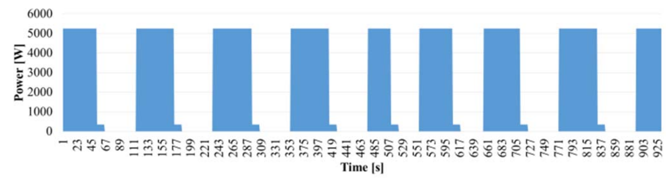

Fig. 7. The air conditioner power variation during the tests for Day-1.

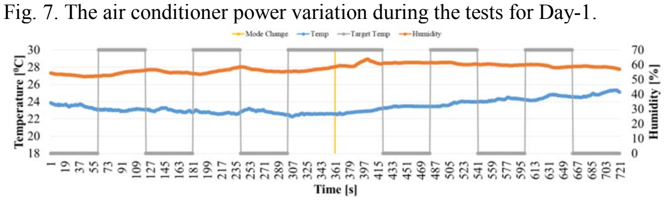

Fig. 8. The ambient meteorological conditions during the tests for Day-2.

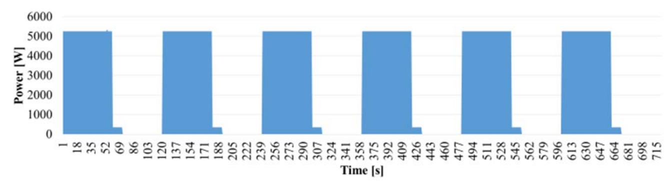

Fig. 9. The air conditioner power variation during the tests for Day-2.

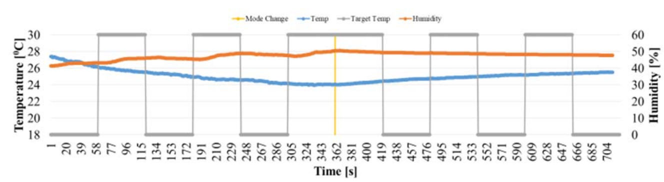

Fig. 10. The ambient meteorological conditions during the tests for Day-3.

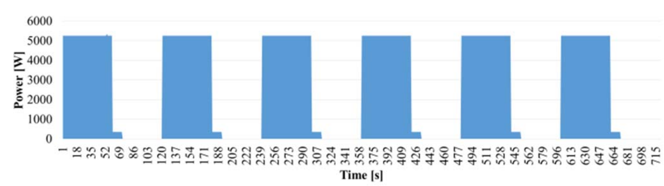

Fig. 11. The air conditioner power variation during the tests for Day-3.

As it can be observed from the given results for different test days, the developed smart thermostat that acts as an end-node device from the system operator point of view in a thermostatically controllable appliances oriented direct load control based demand response program can successfully convert the varying target temperature manipulations to the end-user premise in all conditions. Accordingly, the indoor dynamics and the relevant power consumption can be manipulated with the input conveyed by the system operator, which confirms that the proposed structure can conceptually be employed in such applications.

IV. Concluding Remarks

The role of responsive demand side grows gradually in electric power system operation in terms of increasing the operational flexibility to enhance the effectiveness and economy of electric energy delivery. The activation of formerly inelastic demand side in power system operation is mainly realized by effective demand response programs and direct load control based demand response programs currently play a major role in this manner. In this study, an end-node equipment for such direct load control based demand response programs especially targeting the air conditioner loads was proposed. The concept was experimentally analyzed under different test day conditions and the results depicted that the proposed structure successfully acted as a part of the whole demand response program implementation structure from the system operator point of view. The future extension of this study may consider the implementation of such a demand response scheme for application on consumers consisting of a group (e.g. a microgrid, building block etc.), and the corresponding communication scheme modifications required.

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