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Control of Electric Vehicles Charging without Communication Infrastructure

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***Abstract*— This paper presents a study of controlled charging of electric vehicles (EVs) using a fuzzy logic controller. The controller regulates the charging power according to the state of charge (SoC) of EV and the voltage at the point of connection of EV charger. The objective of the controller is to charge EVs while keeping the voltage of different distribution system points within the acceptable limits. Most of the proposed methods for controlled charging of EVs depend on the availability of the communication infrastructure which enables communication between utility operator and EV chargers which is not available in the current distribution networks and requires a huge investment. So, an autonomous controller which does not need communication infrastructure is developed in this study. The controller is designed to charge EVs without violating the voltage limits which can occur in case of uncontrolled charging of EVs. The effectiveness of the controller is tested on a residential low voltage (LV) distribution network and the simulations are executed with MATLAB/SIMULINK. The network performance in case of controlled charging of EVs is compared with the uncontrolled charging of EVs and the base case when no EVs are connected. The results demonstrate the distinction of the proposed controlled charging method in terms of total power demand, transformer loading, cable loading, and voltage profile over uncontrolled charging.**

Keywords—Distribution network, electric vehicles, uncontrolled charging, controlled charging, fuzzy logic control.

I. INTRODUCTION

There is an international concern about climate change, global warming, greenhouse gas (GHG) emissions, and environmental protection [1]. Most of these issues resulted from the way we use energy. 24% of the CO_2 emissions are produced by transportation sector [2]. EVs are proposed as one of the hopeful solutions to tackle these problems but they still must overcome some considerable barriers to obtain social acceptance and to gain significant market penetration. EVs use energy in an environmentally friendly way. It is expected that EVs will be used a lot in the near future due to their numerous advantages compared with conventional vehicles powered by petrol [3].

The widespread of EVs represents a challenge to the electric utilities because all these new loads represented in EVs will charge from the electricity grid. It is expected that with the spread of EVs it will have a negative effect on the distribution networks. Therefore, comprehensive studies of the EVs charging impacts on the whole power system and especially on the distribution networks are needed [4]–[6]. Also, research studies for developing solutions to the EVs charging impacts on distribution networks should be performed [7]–[9].

Various techniques for controlling EV charging were proposed to reduce the expected negative impacts due to uncontrolled EV charging and for optimal utilization of the distribution system. They can be classified into three categories: centralized charging control, decentralized charging control, and autonomous charging control [10]. In centralized control, the information about the system loading and constraints, electricity market prices, EVs status and their owner's preference are collected and processed by the central controller and the set points are sent to the controlled devices. In decentralized or distributed charging control, a reduced computational burden and communication infrastructure are used. In this type of control, the system operator sends signals to make participating EVs do a specific action and no private information is sent to the system operator. In autonomous charging control the charging and discharging rates depend on local inputs with no need of communication between the system operator and EV charger which can be the first step in the effective integration of a huge number of EVs in the distribution networks in its current state. Also, it can be used at the lowest levels of centralized or decentralized control because it can reduce the communication traffic to V2G aggregator. Autonomous control can be considered as the only option for distribution systems with no available communication infrastructure

Several studies proposed fuzzy logic-based methods to control EV charging. In [11] control of EV charging using online fuzzy coordination algorithm was executed. The objective was to reduce energy generation cost and grid losses as well as keeping node voltage and maximum demand in the acceptable limits. In [12] a fuzzy logic-based algorithm was proposed with system minimum voltage, battery SoC, and energy prices as inputs and charging power as an output. The objective was to improve the voltage profile and maintain the distribution system minimum voltage within the acceptable values. In [13] a fuzzy logic controller was used to control the plug-in hybrid electric vehicles (PHEV) charging. The controller inputs were the SoC of PHEV and real time voltage signal sent by

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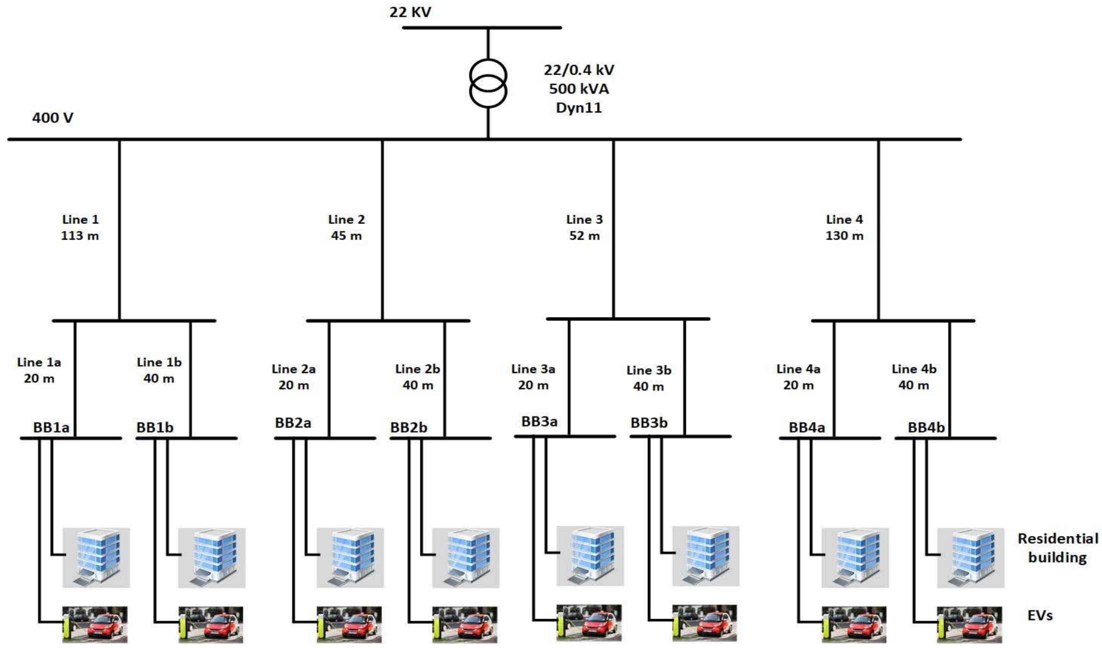

Fig. 1 Single line diagram of the LV distribution network.

distribution management system through the communication lines. Depending on the two inputs, the controller determines the charging level of PHEV.

This paper presents EV charging management method based on fuzzy logic controller. An autonomous fuzzy controller is used to control the EV charging rate depending on two inputs, the voltage at the point of connection and SoC of EV battery. This controller does not need communication infrastructure which is a significant advantage. The total power demand, transformer loading, cable loading, voltage profile of the LV distribution network for the base case, uncontrolled charging, and controlled charging are investigated and compared.

II. MODELING AND SIMULATION

A. LV Distribution Network

The single line diagram of the residential LV distribution network in New Toshka city, Aswan, Egypt which is used in this study is shown in Fig. 1. It is a radial LV distribution network and supplied from medium voltage (MV) network through a 500 kVA 22/0.4 kV Dyn11 transformer. Four main (primary) cables (feeders) are connected to the transformer LV side, each of these primary cables is connected to two smaller (secondary) cables, and each secondary cable supplies one building. The distribution network supplies eight residential buildings and there are 12 apartment in each building, so the total number of residential consumers supplied by the LV distribution network is 96. The voltage unbalance is not considered in this study; therefore, the single-phase loads are assumed to be distributed equally on the three phases. The load power is 4 kVA and 0.9 lagging power factor. All the distribution network components parameters and data are provided in [14]. Fig. 2 shows the daily load profile of the residential consumers [15], where 1 pu is equivalent to 4 kVA. The EVs of these apartment residents will be charged from the distribution network when they arrive to home.

B. EV load

A three-phase EV charger with 6.6 kW power rating and 90% efficiency is used in this study. The capacity of EV battery is 24 kWh as in Nissan Leaf [16]. The SoC of EV battery at charging start time is assumed to be 20%. This assumption considers that EV battery lifespan increases with using only 80% of its total capacity and it represents worst scenario from the network point of view because the battery is approximately empty which needs high energy to be fully charged. SoC of EV battery is a ratio between the stored energy and the nominal capacity of battery (1). The required energy to fully charge EV battery can be calculated by (2). By considering the EV charger efficiency the actual amount of energy drawn from the network can be calculated by (3). With this EV charger power rating, an EV can be fully charged (100% SoC) in 3 hours with uncontrolled charging.

$$\text{SOC [\%]} = \frac{\mathit{Actual\ stored\ Ah\ capacity}}{\mathit{Nominal\ Ah\ capacity\ of\ battery}} * 100 \quad (1)$$

$$E_C = \left(1 - \frac{SOC}{100}\right) \times C \quad (2)$$

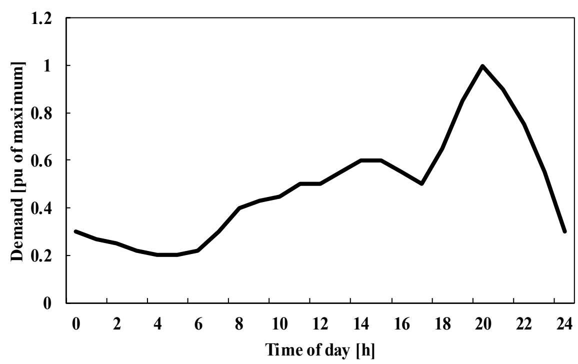

Fig. 2 Daily load curve for the residential loads.

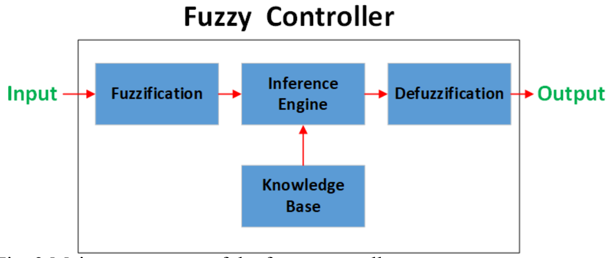

Fig. 3 Main components of the fuzzy controller.

$$E_g = \frac{E_C}{\eta} \tag{3}$$

where E_C is the required amount of energy to fully charge the EV battery; C is capacity of EV battery in kWh; E_g is the amount of electrical energy supplied from the network; η is efficiency of EV charger.

C. *Fuzzy Logic Controller*

The fuzzy logic controller [17], [18] is one of Artificial Intelligence (AI) based control systems which try to use the human reasoning in controller design. The fuzzy controller is easy to design even for complex systems because it depends on designer knowledge and experience and no mathematical model of the system to be controlled is needed. The controller design simplicity is very important for future smart grid which is expected to be very complex. The process of choosing the proper membership function shape is not an easy task and the only experience may help the designer. The designer can choose from many shapes of membership functions. There are triangular, trapezoidal, gaussian, sigmoidal, polynomial forms. Triangular and trapezoidal forms are the most commonly used due to their linearity and simplicity and they were used in the controller design. The fuzzy controller consists of 4 main components as shown in Fig. 3.

D. *Charging Methods*

1) *Uncontrolled Charging*

In this case, the EV starts the charging immediately when it reaches home at the maximum charging power (6.6 kW in this case) to fully charge the EV battery as soon as possible (4). This case shows the effects of integrating many EVs in LV distribution networks without charging management or coordination. EV charging with 50% penetration level is investigated which is equivalent to 48 EVs. The penetration level can be calculated using (5). The charging start time follows a normal distribution (6) with 18:00 mean (μ) and 5 hours standard deviation (σ) as shown in Fig. 4 [19]. Fig. 5 shows the exact number of EVs that will start charging at each hour during the day. The impact of uncontrolled EV charging on the distribution system total power demand, transformer loading, cable loading, the voltage at the furthest point from transformer were investigated.

$$t_{charging} = t_{arrival} \tag{4}$$

$$EVs\ Penetration\ Level[\%] = \frac{Number\ of\ EVs}{Number\ of\ Loads} \times 100 \tag{5}$$

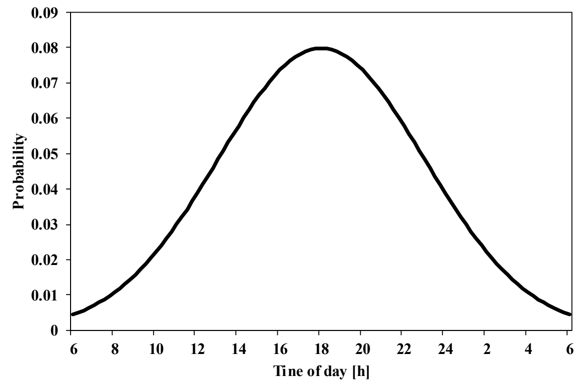

Fig. 4 Probability distribution of charging start time of EVs.

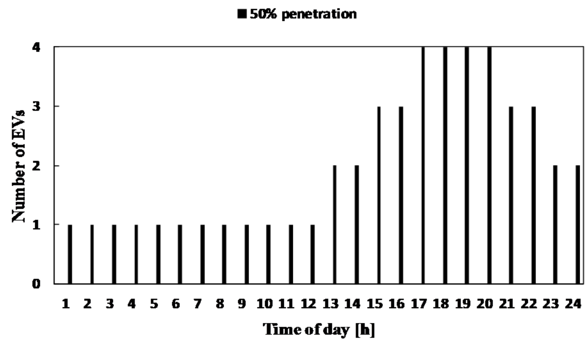

Fig. 5 Charging start time of EVs.

$$f(t,\mu,\sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(t-\mu)^2 / (2\sigma^2)} \tag{6}$$

2) *Controlled Charging*

In this case, the charging start time of EVs is the same as in uncontrolled charging, but the charging power is not constant during the EV charging period and is controlled by the fuzzy logic controller. The charging power depends on the distribution network condition represented in the voltage at the point of connection and the SoC of EV. The charging power depends on the controller design (membership functions and rules), too. The controller can maximize electric utility benefits by keeping the system operating under the acceptable conditions and prevent or delay system upgrade. There are two inputs to the EV charging autonomous controller and one output. Each input and the output have membership functions. The controller inputs are the SoC of the EV battery and the voltage at the point of connection of the EV charger. At the start of the charging, the EV with a lower SoC has a charging priority and will be charged at a faster rate and higher charging power compared with the EV with higher SoC. The voltage input is used as a signal which indicates the loading condition of the distribution network. During high loading condition, high currents flow through the cables which cause higher voltage drop, so the voltage decrease. When the voltage is high the charging power is high compared with that when the voltage is low. The controller output (charging power) depends on the values of the two inputs and the controller design (membership functions and rules).

The universe of discourse of the first input (SoC), second input (voltage) and output (charging power) is divided into five membership functions (two trapezoidal and

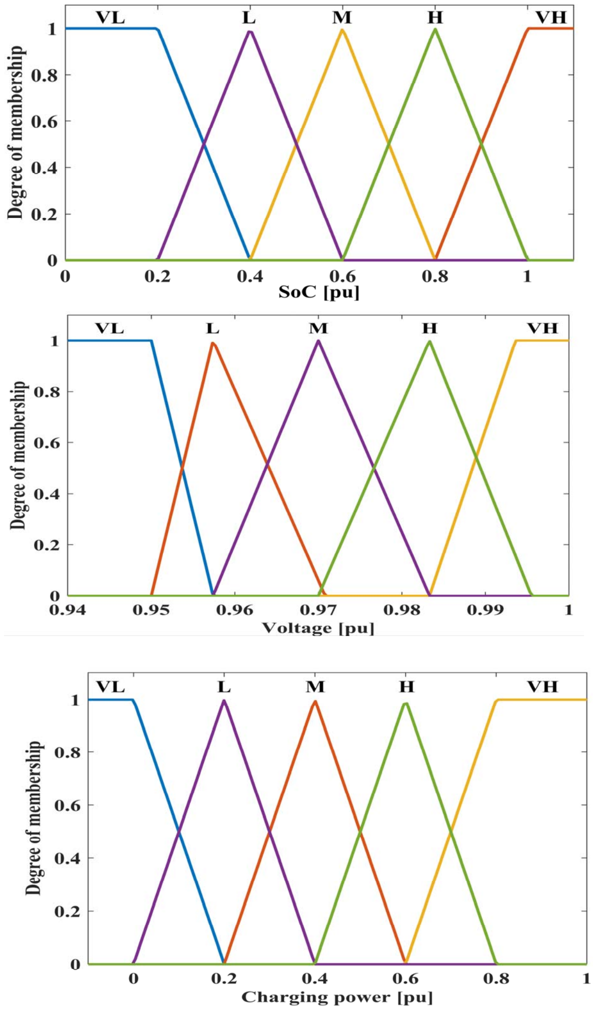

Fig. 6 Membership functions of inputs and output.

three triangular) Very Low (VL), Low (L), Medium (M), High (H) and Very High (VH) as shown in Fig. 6. Table I shows the controller knowledge base rules. All the input and output control signals are in per unit. Therefore, the output from the fuzzy logic controller is multiplied by the maximum charging power to get the real EV charging power value. Fig. 7 shows the fuzzy controller model in MATLAB/SIMULINK with voltage and SoC inputs and per unit charging power output which is multiplied by 6.6 kW gain. A saturation limits block is used to guarantee unidirectional power flow in all conditions. Fig. 8 shows a three-dimensional (3-D) visualization of the control space. The surface viewer shows the inputs and output relation.

TABLE I. FUZZY CONTROLLER KNOWLEDGE BASE RULES

V / SoC	VL	L	M	H	VH
VL	VL	L	H	VH	VH
L	VL	L	M	H	VH
M	VL	L	M	H	VH
H	VL	VL	L	M	H
VH	VL	VL	L	M	H

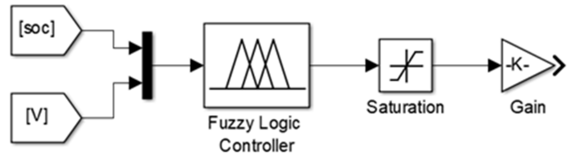

Fig. 7 Controller MATLAB/SIMULINK model.

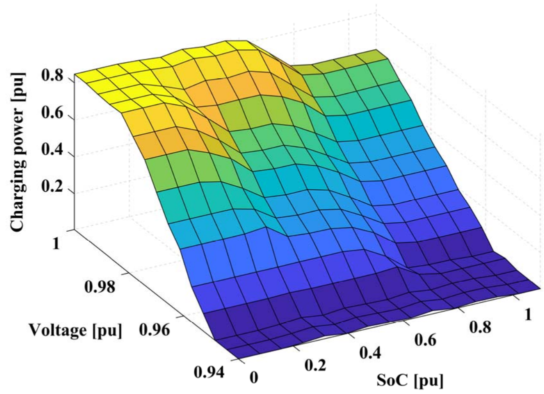

Fig. 8 3-D surface viewer.

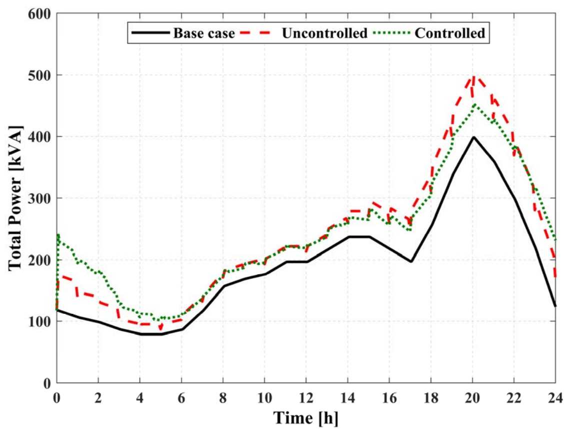

Fig. 9 Total power demand for the base case, uncontrolled charging, and controlled charging

III. RESULTS AND DISCUSSION

In the following sections, the LV distribution network performance when EV charging is managed by the fuzzy controller is presented and compared with uncontrolled EV charging when EVs are charging with maximum charging power to be fully charged as soon as possible. Also, the system performance in the base case where no EVs are connected for charging is investigated.

A. Total Power Demand

Fig. 9 shows the distribution network total power demand during the day for the three cases, base case, uncontrolled charging, and controlled charging with the proposed fuzzy controller. It is clear that for uncontrolled charging, peak power demand at 20:00 increased by 100 kVA compared with the base case. On the other hand, for controlled charging case, the peak demand increased by only 50 kVA compared with the base case which is less than the increasing in case of uncontrolled charging. Controlled charging resulted in shifting part of the EV loads from peak demand period to lower demand period which is called valley filling.

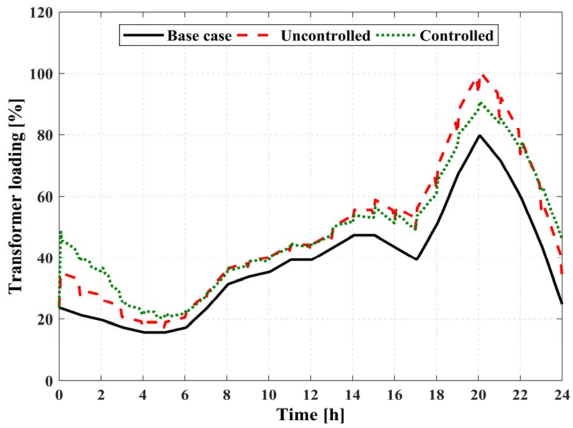

Fig. 10 Transformer loading for the base case, uncontrolled charging, and controlled charging.

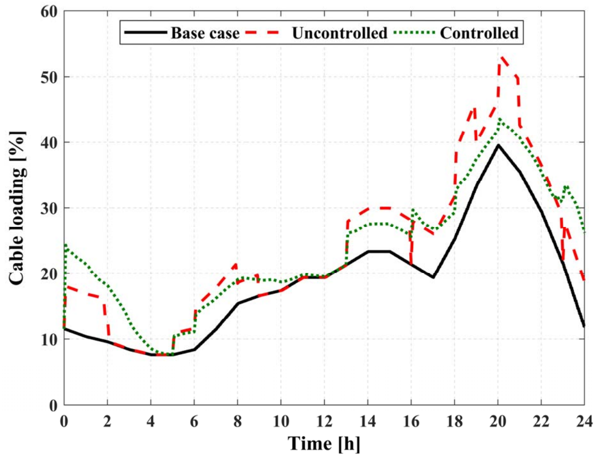

Fig. 11 Cable loading for the base case, uncontrolled charging, and controlled charging.

B. Transformer Loading

The transformer loading during the day of the three investigated cases is shown in Fig. 10. It can be observed that the transformer highest loading was recorded with uncontrolled EV charging and reached 100% of its power rating at 20:00 which is the maximum permissible limit for the transformer. This means transformer upgrade is required for EV penetration levels of more than 50%. On the contrary, only 90% transformer loading was recorded for controlled EV charging because EVs were not charging with the maximum charging power at peak demand time.

C. Cables Loading

The studied distribution network has many cables supplying different buildings and EV loads, but they have similar loading. Therefore, to avoid the repetition of the results, only cable 4 loading was investigated. The cable loading during the day is shown in Fig. 11. The cable was lightly loaded in all the three investigated cases, but higher loading was recorded for uncontrolled charging (50%) compared with controlled charging (40%)

D. Voltage at feeder's endpoints

The voltage profile of the furthest point from transformer was investigated. This point is expected to have the lowest voltage value. According to ANSI standard [20], the voltage should be kept within +/-5% of the rated voltage. The fuzzy controller is designed to prevent voltage from exceeding this limit. EVs charge with high power when the voltage is high (near 1 pu), charge with low power when the voltage is low (near 0.95 p.u), and stop charging when the voltage is less than 0.95 pu As shown in Fig. 12, EV loads result in higher voltage drop in the distribution network and the lower voltage was recorded during the day for uncontrolled charging compared with the base case and reached 0.95 pu at 20:00. In opposition, controlled charging has a better voltage profile compared with uncontrolled charging because the charging power changes with the change in system demand and the lowest voltage value recorded was 0.96 at 20:00

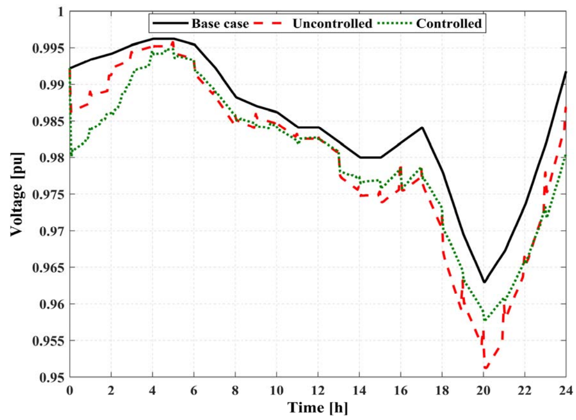

Fig. 12 Voltage at cable endpoint for the base case, uncontrolled charging, and controlled charging.

IV. CONCLUSIONS

In this study, controlled charging of EVs was performed using a fuzzy logic controller. Firstly, an autonomous charging controller was studied. The controller does not need any communication infrastructure because it depends on local inputs. The controller inputs are the voltage at the point of connection and SoC of EV battery. The controller output is the charging power. Total power demand, transformer loading, cable loading, and the voltage at the cable end point were investigated for the base case (where no EVs were connected), uncontrolled charging, and controlled charging. It was concluded that:

- Controlled charging reduced the total power demand peak compared with uncontrolled charging and made a valley filling by shifting some of EVs charging to off-peak period.
- Controlled charging reduced the maximum transformer loading during the day by 10% compared with uncontrolled charging.
- The cable was lightly loaded for uncontrolled and controlled charging, but higher loading was recorded for uncontrolled charging (50%) compared with controlled charging (40%).
- Controlled charging improved the voltage profile compared with uncontrolled charging.

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