SCHEDULING ALGORITHM OF A SMART DISTRIBUTION TRANSFORMER ENERGY MANAGEMENT SYSTEM WITH ELECTRIC VEHICLE HOME CHARGER

BY

PARINYA SONSAARD

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING (ENGINEERING TECHNOLOGY)
SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY
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A Thesis Presented

By
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Submitted to
Sirindhorn International Institute of Technology
Thammasat University
In partial fulfillment of the requirements for the degree of
MASTER OF ENGINEERING (ENGINEERING TECHNOLOGY)

Approved as to style and content by

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MAY 2017

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Abstract

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PARINYA SONSAARD

B.Eng. (Electrical Engineering), Sripatum University, 2005

This thesis studies scheduling algorithm of a smart distribution transformer energy management system with electric vehicle home charger. Increasing in fuel prices and environmental concerns such as global warming have led to alterations in the configuration of power systems. Electric vehicles (EV) are increasingly utilized and charged their batteries at homes. The increasing of electricity demand at home from EV charging load (EV load) may overload and damage distribution grid or distribution transformer (DTR). In this work, we focus on optimization of a smart distribution transformer energy management system (TEMS) with EV load, subject to constraints of DTR loading and voltage imbalance of the DTR. The thesis assumes that there is a two-way real-time communication infrastructure among the DTR's and EV loads. It uses for communicatation between a utility and a customer. We propose an algorithm to schedule EV loads to maximize the minimum final state of charge of all EV's batteries.

From the simulation results, the proposed algorithm (TEMS) can manage the DTR load that meets its loading and voltage imbalance constraints. In addition, the energy tariff is adjusted dynamically and the utility is allowed to manage special loads such as EV charging loads for system stability and impact to the base load and the distribution grid.

Keywords: Smart Grid, Transformer Energy Management System, Electric Vehicle Charging

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Chapter 1
Introduction

1.1 Statement of Problem

As electric vehicles (EV) are going to enter Thailand market in the near future and most of the EVs will charge their batteries at homes. There is a need to understand the impact of EV charging loads on the electricity distribution infrastructure, which is operated by Provincial Electricity Authority (PEA), a major utility in Thailand. As same as in other countries, EVs in Thailand are a main driver in smart grid to reduce CO_2 emission and improve energy efficiency [Provincial Electricity Authority, 2011]. Increasing usage of EVs are expected to significantly raise the electricity demand at home. It may overload and cause heat damages to the distribution grid and, in particular, the distribution transformer, which is a costly component in the medium and low voltage distribution grid.

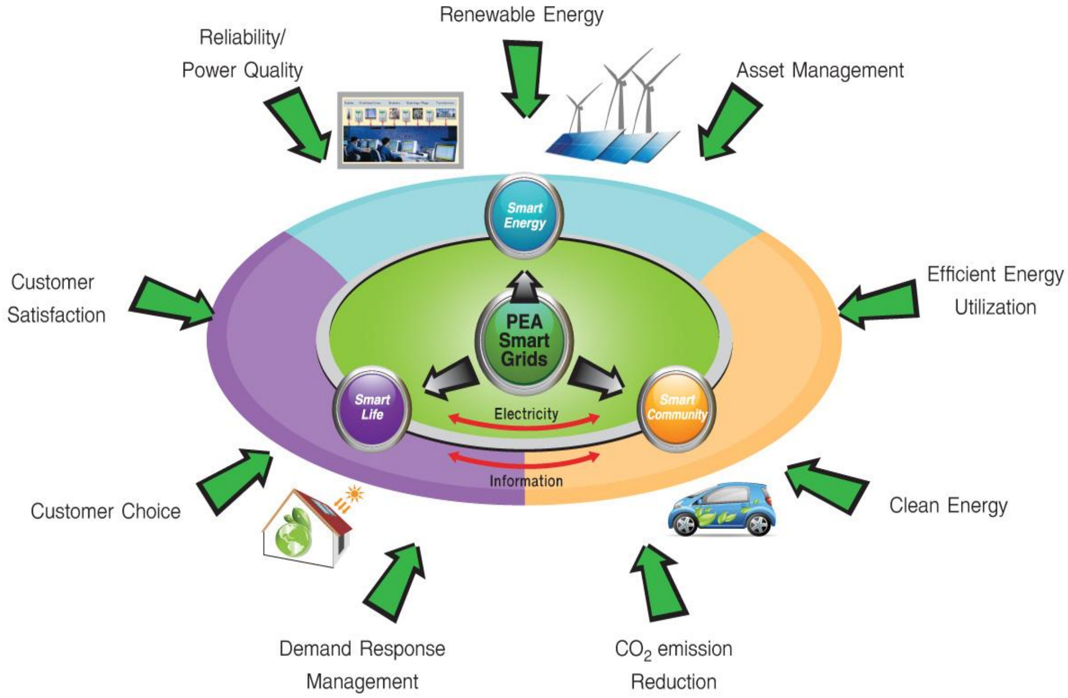

Figure 1.1 PEA Smart Grid Drivers

Figure 1.1 shows the main drivers for PEA Smart Grid. PEA is a utility provider under the Ministry of the Interior. Its major objective is to provide and distribute electricity and services for customers with sufficiency, efficiency and reliability, covering 74 provinces area 510,000 km^2 (99.98%) and 18.17 million customers [Provincial Electricity Authority, 2017]. PEA has planned to develop the PEA Smart Grid project to improve their electric distribution system.

1.2 Objectives of the Study

Since PEA has prepared to support increasing EV loads, the main objective of this thesis is to study how to maximize the state of charge (SOC) of EV's batteries on a distribution transformer (DTR). Specifically, the objectives are as follows:

1. To study the loading and voltage imbalance impact of EV home chargers (EV load) on distribution transformer.
2. To develop a control algorithm of centralized EV load management system on distribution transformer.
3. To develop an optimization method of distribution transformer energy management system.

1.3 Significance of Study

Due to the increasing of electricity demand from EV loads, some distribution transformer could be overloaded or heat damaged. Then the utility provider should improve its own distribution grids. An algorithm for resolve that issue is a distribution transformer energy management system (TEMS) that can manage EV loads and base loads. TEMS is used to control the load of distribution transformer in order to limit its energization not more than its rate. The algorithm will optimize current load including EV load with the new entrant EV that request to charge. If the request do not more than system's capacity, it will allow the new entrant EV to be charged otherwise do not charge. For this algorithm, PEA have to install some information and communication infrastructure to communicate between distribution transformer and

EV loads as shown in Figure 1.2. Energy tariff will be changed and allow a utility provider to manage special load such as EV loads for maintaining system stability that do not impact base load.

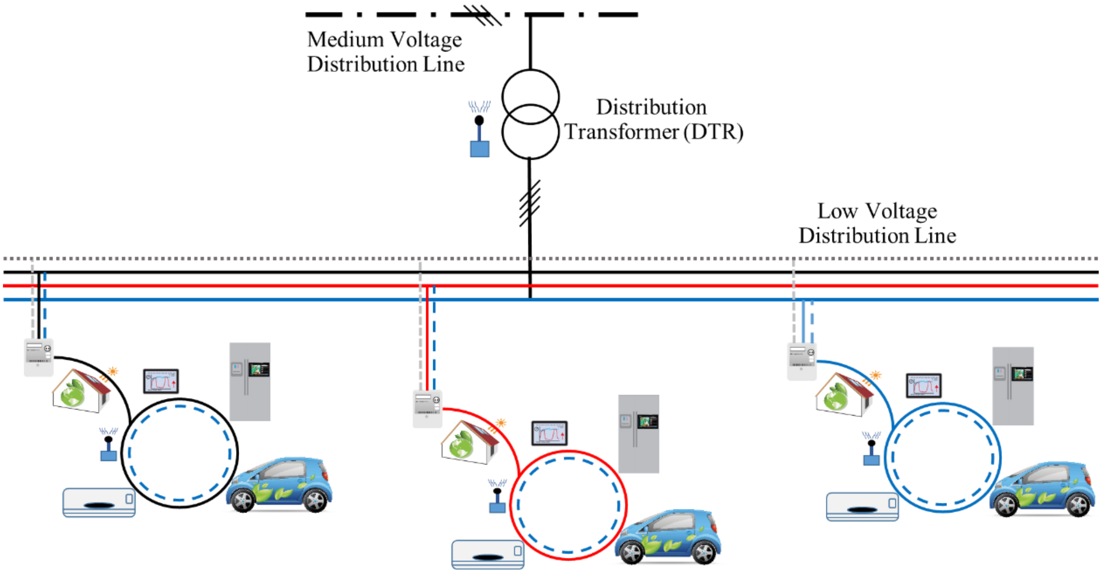

Figure 1.2 EV charger architecture with advanced metering infrastructure

1.4 Thesis Organization

This thesis starts with an introduction of the study. In chapter 2, we study about technology of EV charger, residential load profile, limitation of DTR, and Thailand electricity tariffs for residential. Then we describe the impacts that affect distribution transformer. Chapter 3 describes the development of the simulation process in this thesis. Then, we validate the model by using the DIgSILENT software with DPL script. Chapter 4 shows the simulation result of investigating scenarios from the proposed algorithm. Finally, we conclude the thesis and discuss some future works in chapter 5.

Chapter 2
Literature Review

In this chapter, we discuss the background and literature review. First, we explain the electric vehicle (EV) and charging technology. Second, we discuss load profile that includes a base load (residential load) and an EV load. Then, we discuss limitations of distribution transformer from its insulation aging. After that, we discuss voltage imbalance impact of EV load. Finally, we show some related work from other researchers.

2.1 Electric Vehicle and Charger Technology

The electric vehicle is a vehicle which is propelled completely (BEV) or partially (PEV/PHEV) by an electric motor instead of an internal combustion engine. Electrical energy is from rechargeable batteries or other on-board, or from an external source, including plugging into the grid or solar panel on the roof top. The drive system of EV converts electrical energy that is stored chemically in the battery into mechanical energy to drive the vehicle. All vehicles propelled by an electric motor are categorized as an EV such as electric golf cars, electric bikes, electric scooters, electric motorcycles, electric cars, electric buses, and hybrid electric cars, as shown in Figure 2.1.

Figure 2.1 Types of electric vehicles

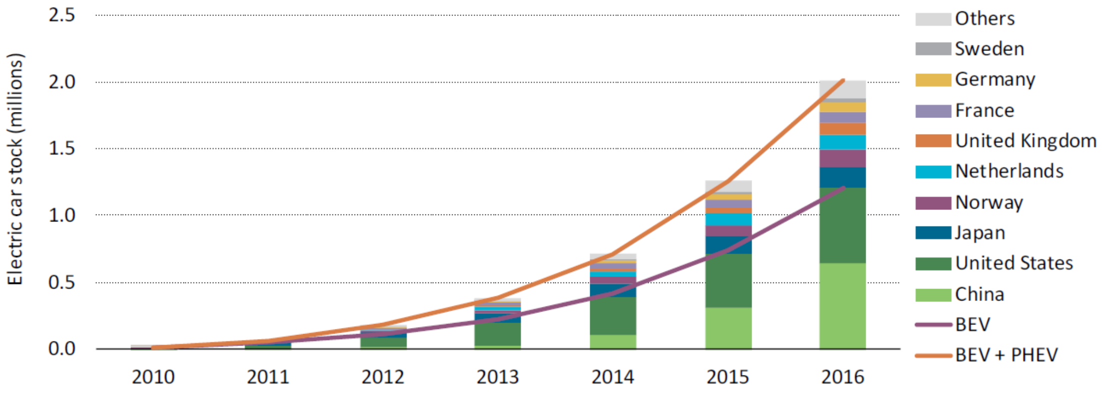

Figure 2.2 Evolution of the global electric car stock, 2010-2016

Figure 2.2 shows the evolution of the global electric car stock from 2010 to 2016 [International Energy Agency, 2017]. It calculated on the cumulative sales since 2005. Currently, several vehicles manufacture launched EVs sale into markets. Table 2.1 shows the key parameters including battery sizes, energy efficiency, driving ranges, and charging power of five available EV in the Europe market [evobsession.com, 2017] and U.S. market [www.fleetcarma.com, 2017].

Table 2.1 Favorite EVs in the Europe and U.S. market in 2016

Maker-Model (type)	Battery size (kWh)	Electric Mode Range (km)	Charge power
Tesla Model S	60-100	390-500	230V 32A 400V 16A
Renault Zoe	22	240	230V 16 A
Nissan LEAF	24	135	230V 16 A
BMW i3 (94 Ah)	27.2	300	230V 16 A
VW e-Golf	24.2	129	240V 30 A

[WIKIPEDIA, 2017]

EV acts as load in a distribution grid, it consumes electrical energy when it plugs into the system grid until unplug or fully charged. Most of EVs nowadays use lithium-ion batteries due to their capability, safety, long life, and reasonable cost [Peng Z. et al., 2012]. According to IEC 61851-1 2010 and IEC 61851-23, EV loads are classified into four modes as shown in Table 2.2. Mode 1 is a normal EV charger which is equip with EV. It can install at the car park at home. Some house may install the mode 2 EV charger instead of mode 1. At the shopping mall, parking lot, and charging station use the mode 2, 3, or 4 as the EV charger.

Table 2.2 Standard charging modes are defined in IEC 61851-1 [2010] and IEC 61851-23 [2014]

Mode	Usage	Phase	Maximum current (A)	Maximum voltage (V)
Mode 1 (AC)	Home charging	1	16	250
		3	16	480
Mode 2 (AC)	Home charging	1	32	250
	Charging station	3	32	480
Mode 3 (AC)	Charging station	1	70	250
		3	63	480
Mode 4 (DC)	Charging station	--	125	500

2.2 Load Profile

2.2.1 Residential Load Profile

Household load profile shown in Figure 2.3 can be defined into different load patterns. It can be defined as a base load of a distribution transformer load profile [Shengnan S., Manisa P., & Saifur R., 2011].

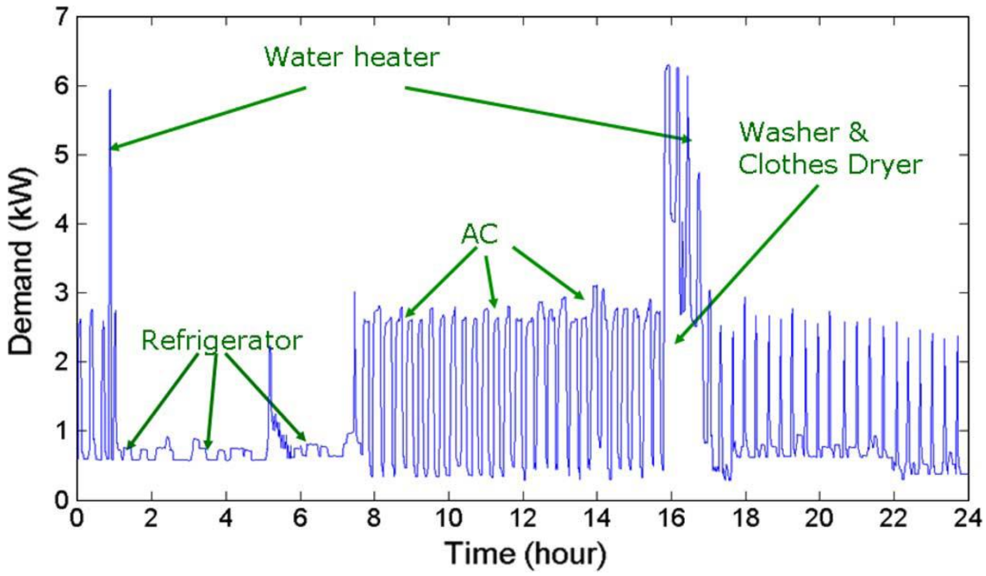

Figure 2.3 24 Hrs. of electric power consumption measured from a house in Virginia

2.2.2 EV Charging Load Profile

EVs charging duration time depends on charging current, EVs battery capacity, and state of charge (SOC). From Figure 2.4, PEA has tested with NISSAN LEAF SOC at the initial SOC at 15%, via a 3.5 kW on-board charger. The battery is it fully charged in 6 Hrs.

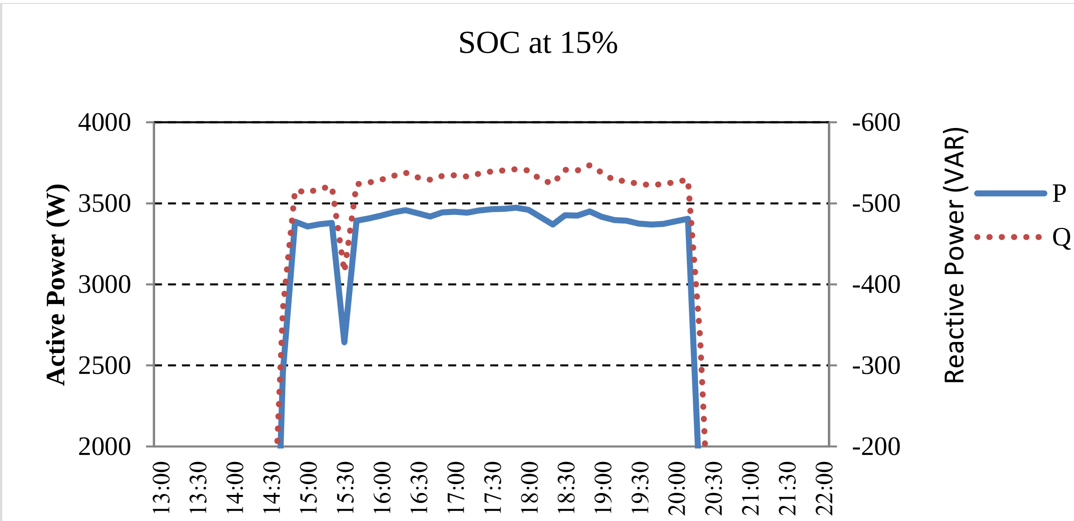

Figure 2.4 Nissan leaf charge test profile at the PEA head quarter from 15% to 100%

2.3 Distribution Transformer

Distribution transformer is the utility's transformer. It is used to step down voltage to the level that is suitable for connecting to customer. It is installed distributedly in the utility distribution system. Distribution transformer serves electrical energy to customers' more than one customer per distribution transformer.

TEMS is a transformer energy management system. It is used to manage the energy that energizes by the distribution transformer to prevent loading impact [Vicini R. et al., 2012]. EV load is a future addition load at DTR. It may highly impact with DTR such as loading and voltage imbalance. Low penetration of EV load may not impact with DTR [Maryam K. et al., 2012]. At the high penetration of EV load, utility has to install the TEMS to prevent loading impact [Chin H. T. et al., 2014], [Alexander D. H. et al., 2013] and postpone an investment in DTR [Shengnan S. et al., 2012].

Most of distribution transformer uses oil for cooling and insulation. For an aging study, an aging is a time function of temperature, moisture content, and oxygen contributions to insulation deterioration can be minimized. Insulation aging equations are: [IEEE Std. C57.91, 2012], [Qiuming G. et al., 2012]

The short-time loading of DTR should not more than 300% of DTR' rated within less than a half hour as shown in the Table 2.3 [IEEE Std. C57.91, 2012].

Table 2.3 Suggested limits of temperature or load for loading above nameplate distribution transformers with 65°C rise

Top-oil temperature	120°C
Hottest-spot conductor temperature	200°C
Short-time loading (1/2 h or less)	300%

The aging acceleration factor (F_{AA}), the rate of transformer insulation aging is accelerated compared with the aging rate at a reference hottest-spot temperature, it is defined as

$$F_{AA} = \exp(\frac{15,000}{383} - \frac{15,000}{\theta_{hs}+273}) \quad (1)$$

where θ_{hs} is hotspot temperature. The reference hottest-spot temperature is 110 °C for 65 °C average winding rise and 95 °C for 55 °C average winding rise transformers. The equivalent aging factor (F_{EQA}) is the average of the aging acceleration over the total time period.

$$F_{EQA} = (\sum_{n=1}^{N} F_{AAn}\Delta t_n)/(\sum_{n=1}^{N} \Delta t_n) \quad (2)$$

where n is an index for the time interval t, N is a total number of time intervals, and Δt_n is a time interval. The percentage of loss of life for operation at a rated hottest-spot temperature as shown (3) where L_{normal} is the normal insulation life. From [Qiuming G. et al., 2012] choose normal life is 180,000 hours.

$$\%\, Loss\ of\ life = \frac{F_{EQA} \times \sum_{n=1}^{N} t \times 100}{L_{normal}} \quad (3)$$

2.4 Voltage Imbalance

Without any control system, low voltage distribution grids or DTR may face with the voltage impact [Chin H. T. et al., 2014] or voltage imbalance impact that may be greater than 2% [Niels L. et al. (2014)]. According to IEC 61000-3-13 [2008], IEC 61000-2-2 [2002], IEEE 1159 [2009], and PRC-PQG-03/2010 [2010], the voltage imbalance is the percentage of the ratio between negative sequence and positive sequence component.

$$\%\, Imbalance = \frac{|V_{neg}|}{|V_{pos}|} \times 100\% \quad (4)$$

where V_{neg} is a negative sequence component and V_{pos} is a positive sequence component.

The voltage imbalance can also be written as

$$\%\, Imbalance = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}} \times 100\% \quad (5)$$

where $$\beta = \frac{|V_{AB}|^4+|V_{BC}|^4+|V_{CA}|^4}{(|V_{AB}|^2+|V_{BC}|^2+|V_{CA}|^2)^2} \times 100\% \qquad (6)$$

where V_{AB}, V_{BC}, and V_{CA} is the RMS voltage phase A-to-B, B-to-C, and C-to-A, respectively. PRC-PQG-03/2010 [2010] limits the voltage imbalance in each voltage level as shown in Table 2.4.

Table 2.4 Voltage imbalance limit in Thailand

Voltage level	Voltage imbalance (%)
230 kV	0.8
69 and 115 kV	1.4
12, 22, 24, and 33 kV	1.8
230/400 V	2.0

[PRC-PQG-03/2010, 2010]

2.5 Thailand Electricity Tariffs for Residential

To charge an EV load at home, a utility will charge a customer as a rate for residential. In the near future, a Thailand utility will launch a special tariff for an EV load. The electricity tariff for residential has two rate as follow. [Provincial Electricity Authority, 2017]

2.5.1 Normal Rate

1. Consume up to 150 kWh. Per Month				Energy Charge (Baht/kWh)
First	15	kWh.	(0 - 15th)	2.3488
Next	10	kWh.	(16th - 25th)	2.9882
Next	10	kWh.	(26th - 35th)	3.2405
Next	65	kWh.	(36th - 100th)	3.6237
Next	50	kWh.	(101st - 150th)	3.7171
Next	250	kWh.	(151st – 400th)	4.2218
Over	400	kWh.	(401st and over)	4.4217

				Energy Charge
2. Consume over 150 kWh. Per Month				(Baht/kWh)
First	150	kWh.	(0 - 150th)	3.2484
Next	250	kWh.	(151st – 400th)	4.2218
Over	400	kWh.	(401st and over)	4.4217

2.5.2 Time of Use Rate

	Energy Charge (Baht/kWh)	
	Peak	Off-Peak
1. At voltage level 22-33 kV	5.1135	2.6037
2. At voltage level lower than 22 kV	5.7982	2.6369

Note: 1. The energy charge do not include a service charge, a Ft, and a Value Added Tax.

2. TOU time:

Peak: 09:00 a.m. – 10:00 p.m. Monday – Friday and Royal Ploughing Ceremony Day

Off-Peak: 10:00 p.m. – 09:00 a.m. Monday – Friday and Royal Ploughing Ceremony Day

: 00:00 a.m. – 11:59 p.m. (24 hrs) Saturday – Sunday, Labor Day, The Royal Ploughing Ceremony Day which is on Saturday or Sunday, Public Holiday (except Compensatory Holiday)

2.6 Satisfaction

Satisfaction is a judgment of a pleasurable level of consumption-related fulfillment, including a level of under fulfillment or over fulfillment [Eric A. et al., 2002].

Chapter 3
Methodology of Study

This chapter presents a methodology of the study. First, we discuss about an assumption of the study. Second, we create a study framework. Third, we model the low voltage distribution system from a base load and an EV then study the loading and voltage imbalance impact with DTR using the DIgSILENT software. Forth, we develop a loading and voltage imbalance module using the MATLAB software, then verify a module with the DIgSILENT software. Fifth, we develop the optimization of distribution transformer energy management system. Then, we develop an EV charging schedule algorithm module. Finally, we models a low voltage distribution system using the DIgSILENT software with the DPL script and compares results between the proposed method and the DIgSILENT software.

3.1 Assumption of Study

This thesis studies the distribution transformer energy management system (TEMS) for support EV loads, we assume the following conditions.

1. A utility has fully installed an Advanced Metering Infrastructure (AMI) for communicating between a utility and customer.
2. A utility can control an addition load such as an EV load.
3. All customers with an EV load use the TOU tariff instead of the Normal tariff.
4. Each a DTR have 60 customers that balance distribution at the low voltage distribution grid.
5. An EV load is a single phase EV charger 3.5 kW.

3.2 Study Framework

The framework of this study can be divided into 3 modules as shown in Figure 3.1. The first module is an EV charging schedule algorithm module. This module generates a charging schedule for a TEMS. The second module is a loading and voltage imbalance calculation module. This module calculates a loading and a voltage imbalance of DTR's load that are a base load and an EV load. The last part is an optimization module. This module calculates the optimal solution of a TEMS.

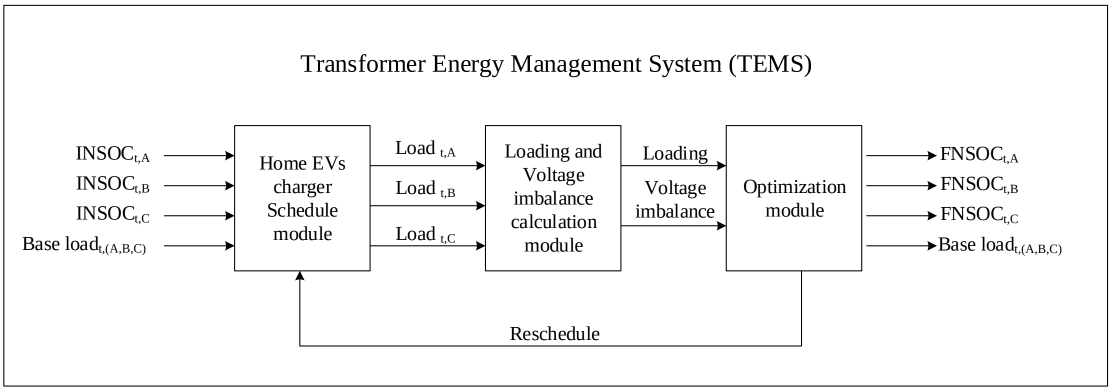

Figure 3.1 The study framework

Where INSOC$_{t,\ A}$, INSOC$_{t,\ B}$, and INSOC$_{t,\ C}$ are an initial state of charge of an EV battery at phase A, B, and C at a time starts period t. Load F$_{t,\ A}$, Load F$_{t,\ B}$, and Load F$_{t,\ C}$ are DTR's load curve. It generates from a base load and the EV load at time period t. FNSOC$_{t,\ A}$, FNSOC$_{t,\ B}$, and FNSOC$_{t,\ C}$ are a final state of charge of an EV battery at phase A, B, and C at time target period t.

The time period of this study is 15 minutes per period, it is a TOU period tariff. In Thailand, TOU tariff are including the on peak (Monday-Friday from 09.00 a.m. to 10.00 p.m.) and the off peak (Monday-Friday from 10.00 p.m. to 09.00 a.m., Saturday-Sunday, National Labor Day and normal public holiday (excluding substitution holiday and Royal Ploughing Day) from 0.00 a.m. to 12.00 p.m. [Provincial Electricity Authority, 2017]

3.3 Load Modeling

The load of this study is a base load and an EV load at period t as follows:

3.3.1 EV Charging Characteristic and Forecast

This method calculates how to charge a battery of EVs that suitable for SOC, CR, and lowest energy cost of customer satisfaction. That method must be suitable for battery lifetime and safety. The charging load as shown in Figure 2.3, it load is 3.5 kW on period t Hrs. When fully charged, it load is 0 kW (SOC =100%).

3.3.2 Initial State of Charge

The initial state of charge is based on the traveling distance of the EVs in the city that it is left-skewed distribution as shown in Figure3.2 [Peng Z. et al., 2012].

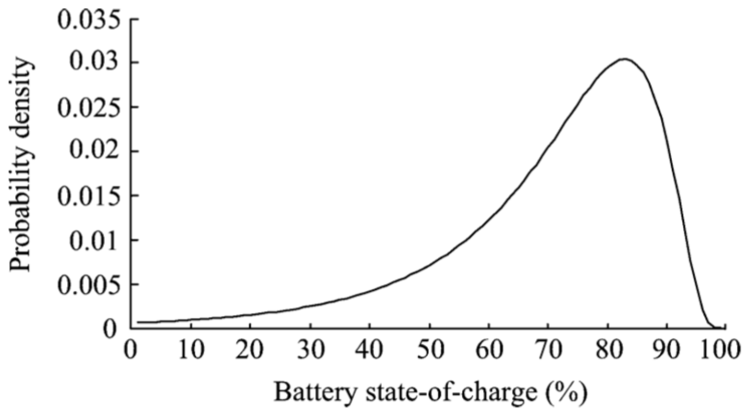

Figure 3.2 Probability density of battery SOC after one day travel

In this study, we use the normal distribution for the initial state of charge because it is the worst case for the loading and voltage imbalance of a DTR.

3.3.3 Distribution Transformer Load Curve

This method determines energy demand from a customer that use via a DTR as a base load and an EV charging. It can determine the number of an EV loads that suitability for DTR each time period. Table 3.1 shows PEA's DTR utilized factor and available capacity for an EV load.

Table 3.1 PEA's DTR utilized factor

Item	DTR size (kVA)	% UF	Available capacity (kVA)	No. of EV per charged	
				Normal	Fast
1	30	25.48	18	5	1
2	50	40.04	24	6	1
3	75	34.85	39	10	2
4	100	34.85	52	13	2
5	160	31.60	88	23	4
6	250	33.95	132	34	5
7	315	33.95	166	43	7
8	400	38.33	197	51	8
9	500	38.33	247	63	10

Remark: %UF from on-site distribution transformer at center region of PEA, PF 0.9, DTR should not energized more than 80%. Normal charger is 3.5 kW and fast Charger is 22 kW.

Figure 3.3 shows load profile of PEA'S DTR, it applies from the PEA load profile of a residential customer at the Central Region 2 [Provincial Electricity Authority, 2013]. It energizes to customers at least 30 customers without an EV load. We assume that it may supply an EV load up to 20 EV load per phase. Figure 3.4 shows, if have 20 EV loads at the same time, DTR may overload at the peak period (09.45 p.m.).

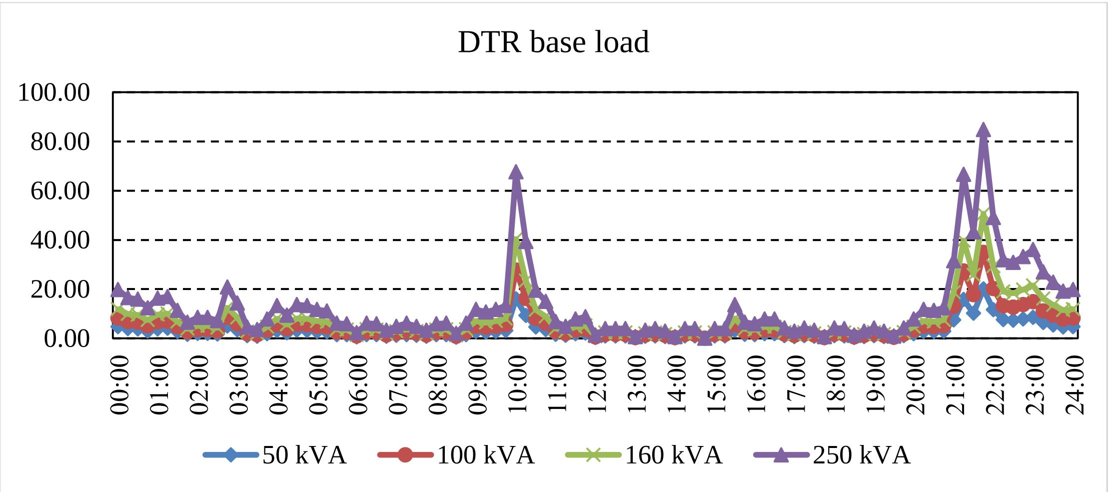

Figure 3.3 PEA's DTR load profile

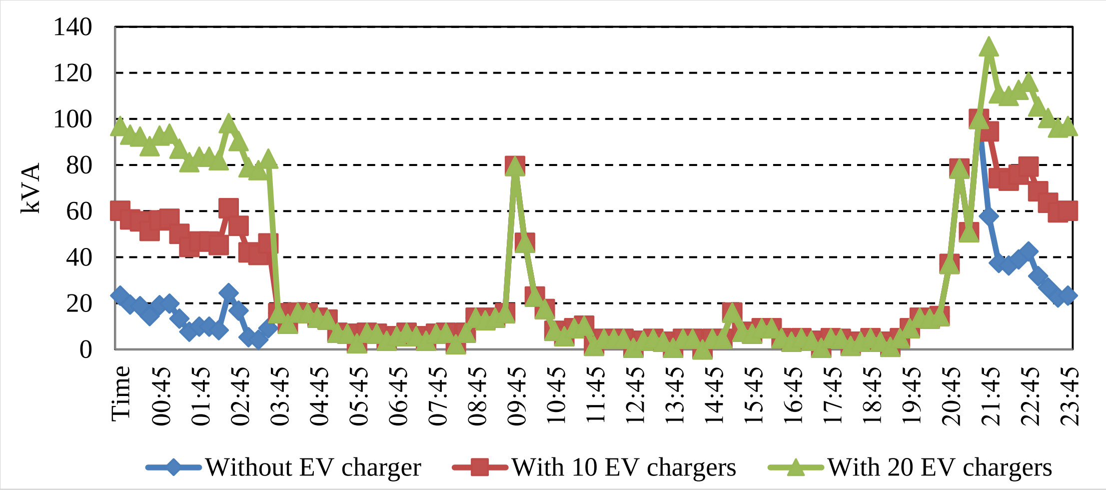

Figure 3.4 100 kVA distribution transformer load profiles with/without an EV load

3.4 Impact of Distribution Transformer Module

In this part, we study the impact of an EV load with DTR using the DIgSILENT software. Then we develop the loading and voltage imbalance module in the MATLAB Software. Finally, we test the module and compare the result with the DIgSILENT software.

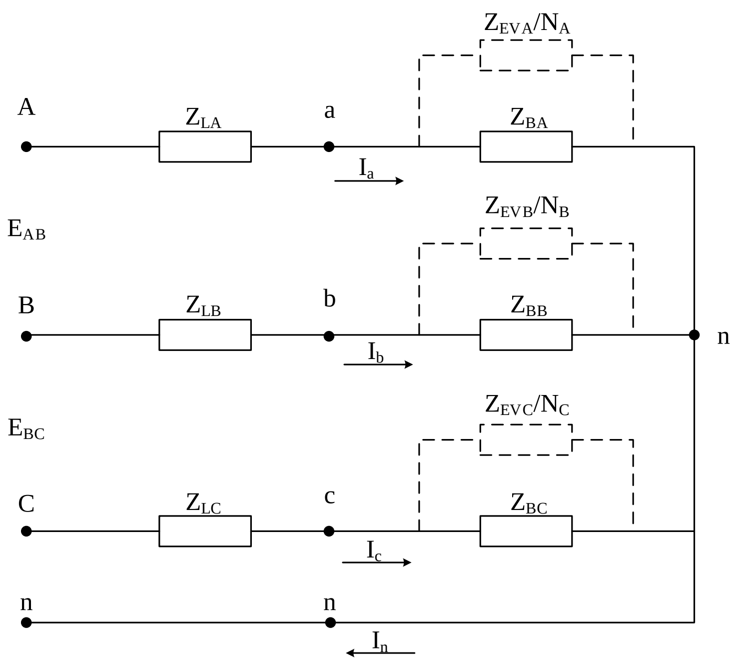

Figure 3.5 Simplified model of the low voltage distribution grid with an EV load

Figure 3.5 shows the simplified model of the low voltage distribution grid with an EV load for setting up the loading and voltage imbalance calculation module. This circuit consists of a line impedance (Z_L), a base load impedance (Z_B), and an EV load impedance (Z_{EV}). We use the Mesh analysis to calculate this circuit. The voltage imbalance can calculate from the equation (4)-(6) [Robbins, A. H. & Miller, W. C., 1995], [Hayt, W. H., Jr. & Kemmerly, J. E., 1993].

3.4.1 Loading and Voltage Imbalance Module Development

A low voltage grid with a 160 kVA DTR configuration in this study are as follows:

1) DTR vector is Dyn11, its impedance is 0.000625+j0.04257663 Ohms/Phase.
2) Customers have distributed from DTR up to 1 km per each side.
3) Line impedance is 0.03415404+j0.04257663 Ohms/Phase/100 m.
4) Each DTR have 60 customers, they have one EV load per each home.
5) Base load impedance is 3 kW and PF 0.95 lagging.
6) EV load impedance is 3.5 kW and PF 0.95 lagging.

From Figure 3.6, it can calculate I_a, I_b, and I_c by using the Mesh analysis. V_{ab}, Vbc, and V_{ca} can calculate by $V_{an} = E_{An}-V_{Lan}$, $V_{bn} = E_{Bn}-V_{Lbn}$, $V_{cn} = E_{Cn}-V_{Lcn}$, and $V_{ab}=V_{an}-V_{bn}$, $V_{bc}=V_{bn}-V_{cn}$, and $V_{ca}=V_{cn}-V_{an}$ [Robbins, A. H. & Miller, W. C., 1995].

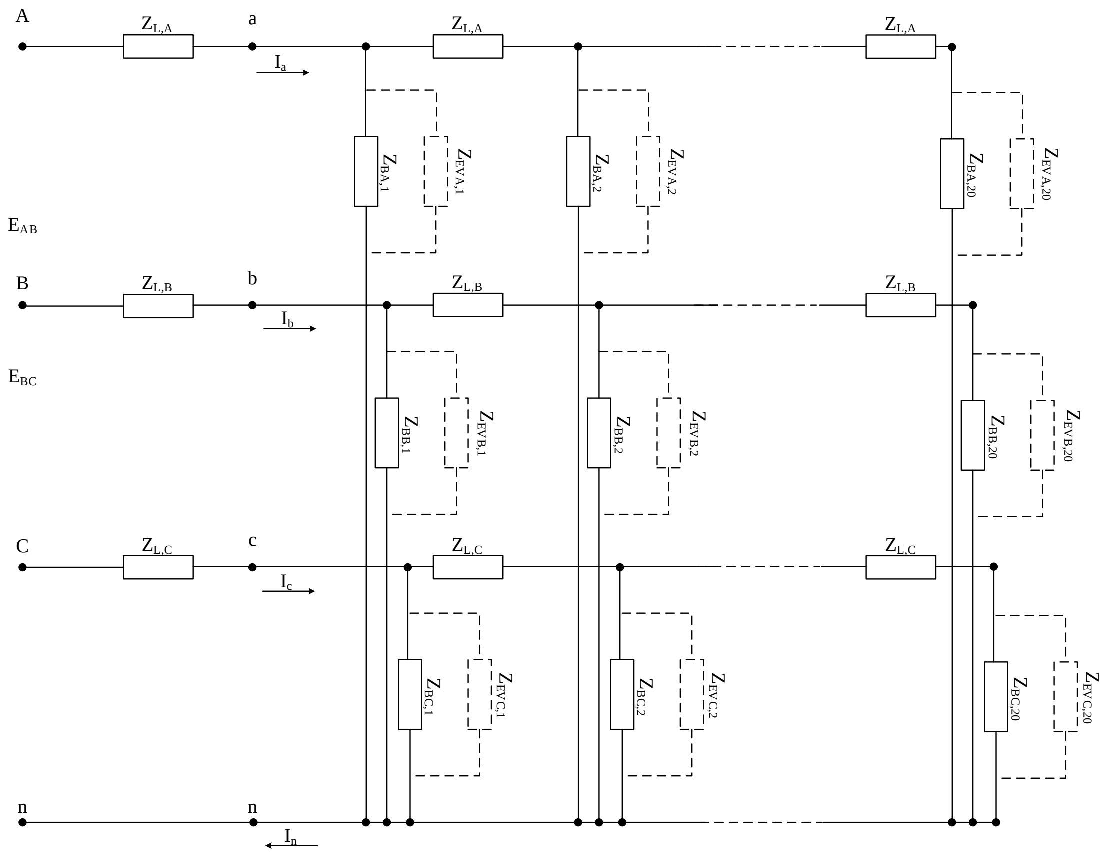

Figure 3.6 Low voltage distribution grid with an EV load

In this part, we investigate the case with/without an EV load to study an impact of EV load without a communication system. Then check the results of a loading and voltage imbalance module. The result of this study is a limitation of an EV load per DTR. A base loads have balanced distribution along a distribution grid. Increasing of the number of EV load at one phase, two phase and three phase as shown in Table 3.2. The investigated study cases are as follows:

Table 3.2 The investigated study cases

Case	EV load		
	Phase A	Phase B	Phase C
1	0	0	0
2	N_{Vary}	N_{Vary}	N_{Vary}
3	N_{Vary}	0	0
4	N_{Full}	N_{Vary}	0
5	N_{Vary}	N_{Vary}	0
6	N_{Vary}	N_{Vary}	N_{Full}
7	N_{Full}	N_{Full}	N_{Vary}

Case 1: Without EV load (Base case)

Case 2: With EV load Penetration at 3 Phase

Case 3: With EV load Penetration at Phase A

Case 4: With EV load at Phase A and Penetration at Phase B

Case 5: With EV load Penetration at Phase A & B

Case 6: With EV load Penetration at Phase A & B when Phase C with EV load

Case 7: With EV load at Phase A & B and Penetration at Phase C

3.4.2 DTR's Loading Simulation Result

Generally, DTR should energize the load not more than 70-80% of its rate, but in the short period DTR can energize up to 120% of its rate without damage. Figure 3.7 shows DTR's base load without an EV load and full load with an EV load curve at 09.45 p.m.

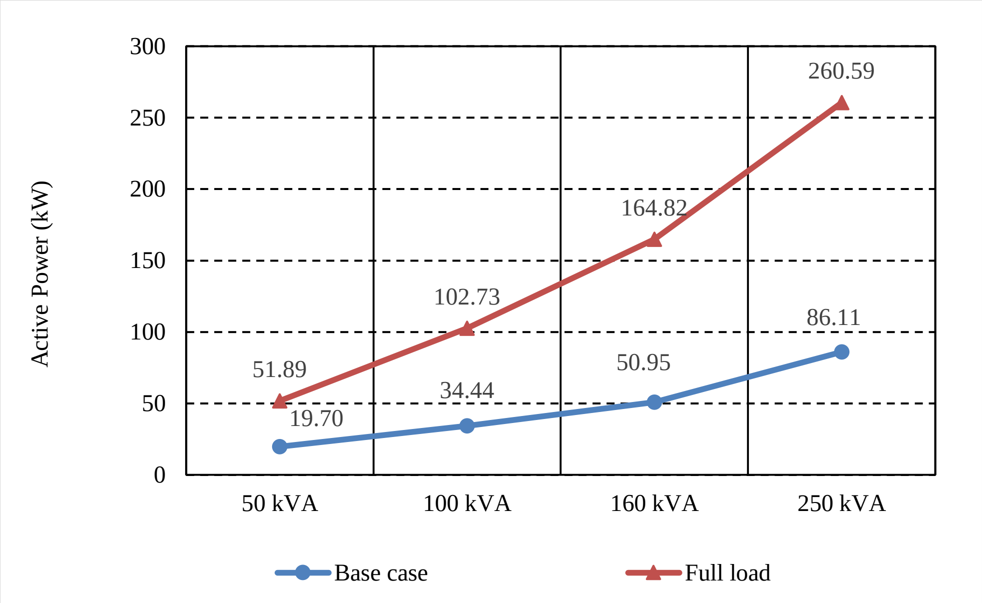

Figure 3.7 DTR loading Base case and Full load

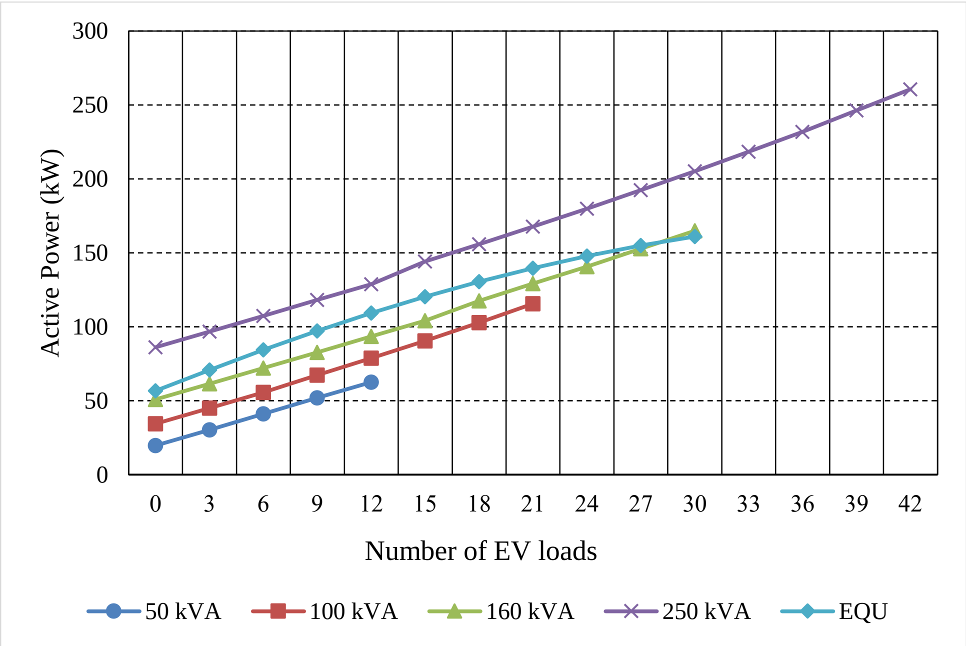

Figure 3.8 DTR loading with EV load curve

Figure 3.8 shows the relation between the number of an EV load and DTR loading of DTR 50, 100, 160, 250 KVA, and equivalent circuit (EQU). The result of DTR 50, 100, 160, and 250 kVA is from the DIgSILENT software. The EQU is the result of the proposed module of the MATLAB software (TEMS). The maximum number of

EV load are 9, 18, 30, 42, and 30 sets per DTR size respectively. This simulation increase the number of an EV load at three phases at the same time to check the maximum number of an EV load per each DTR. This equivalent circuit calculation result is nearly equal to DTR 160 kVA.

3.4.3 DTR's Voltage Imbalance Result

In this study we assume that the base loads are distributed uniformly along the distribution grid, which connects to a DTR without an EV load. Voltage imbalance at the DTR is zero.

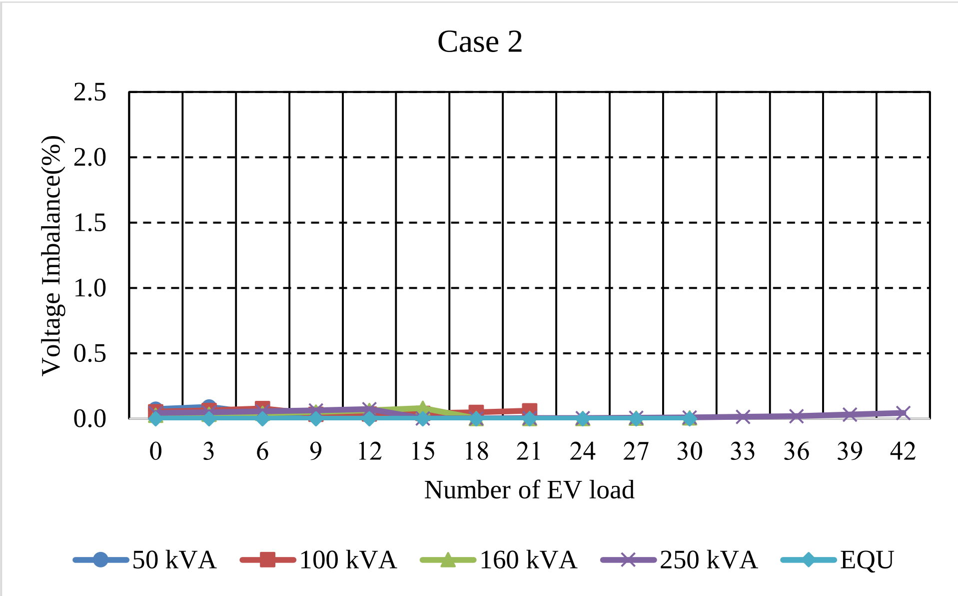

Figure 3.9 Case 2 DTR voltage imbalance

Figure 3.9 shows the relation between the number of an EV load and DTR voltage imbalance of DTR 50, 100, 160, 250 KVA, and EQU in case 2. The maximum number of an EV load are 9, 18, 30, 42, and 30 sets per DTR respectively. This simulation increases the number of an EV load at three phases simultaneously to check the maximum number of an EV load per DTR that does not affect the voltage imbalance.

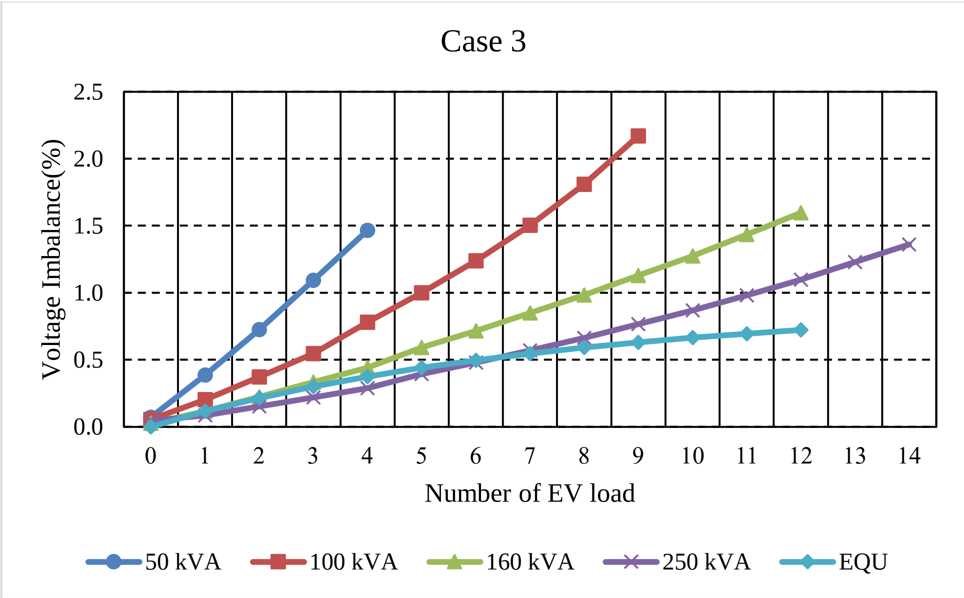

Figure 3.10 Case 3 DTR voltage imbalance

Figure 3.10 to 3.12 show relation between the number of an EV load and DTR voltage imbalance of DTR 50, 100, 160, 250 KVA, and EQU of the case 3. The maximum number of an EV load are 3, 6, 10, 14, and 10 sets per DTR respectively. This simulation increases the number of an EV load at only phase A. The simulation result shows voltage imbalance at a 100 kVA DTR when an EV load connects at phase A up to 9 sets, the voltage imbalance may up to 2%.

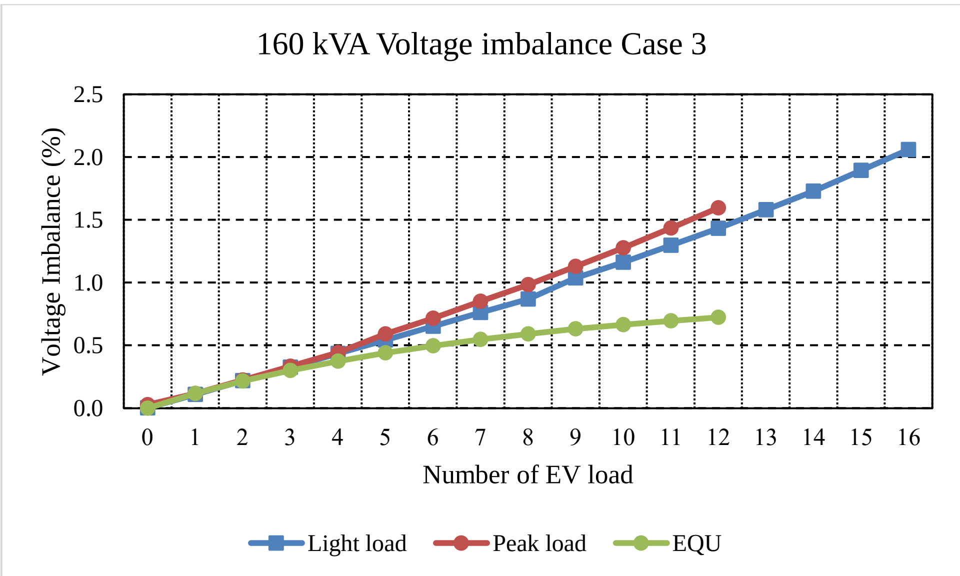

Figure 3.11 Case 3 DTR voltage imbalance in light load and peak load time

Figure 3.11 shows the relation between the number of an EV load and the voltage imbalance of DTR 160 kVA and EQU in the case 3. It shows the voltage imbalance of DTR 160 kVA in the light load time (06.00 p.m.), peak load time (09.45 p.m.), and EQU in peak load time (09.45 p.m.). It shows, if an EV load connects at phase A up to 17 set, it may have voltage imbalance at DTR 160 kVA at light load periodically.

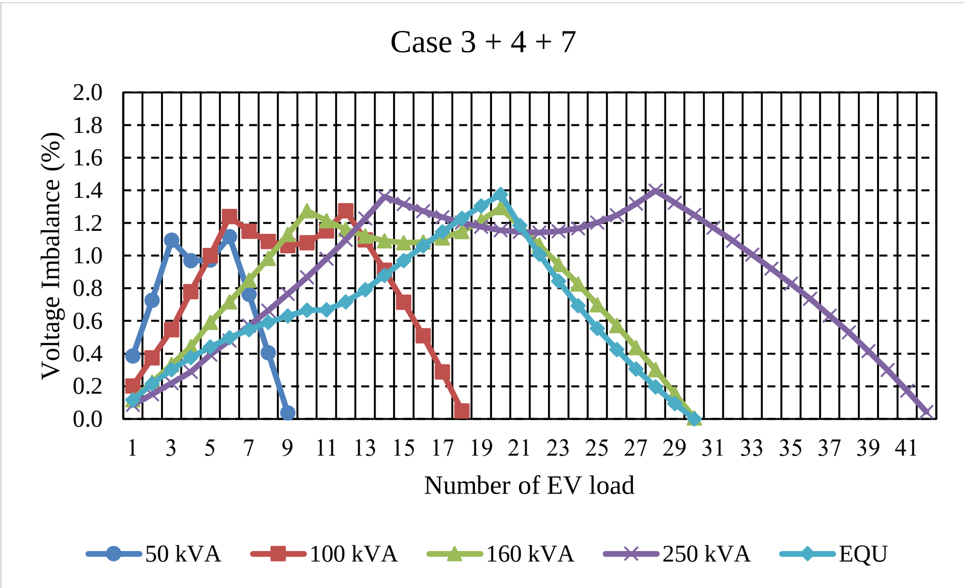

Figure 3.12 DTR voltage imbalance Case 3, 4, and 7

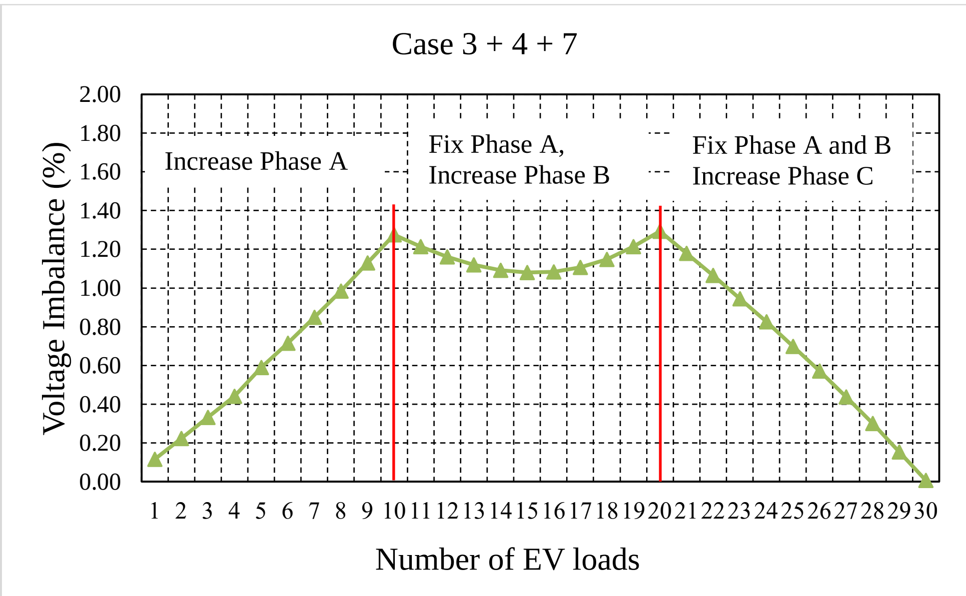

Figure 3.13 DTR 160 kVA voltage imbalance Case 3, 4, and 7

Figure 3.12 and Figure 3.13 show the relation between the number of an EV load and the voltage imbalance in case 3, 4 and 7. Figure 3.12 shows the voltage imbalance curve for all DTR size and Figure 3.13 shows the voltage imbalance curve for DTR 160 kVA. The first part is case 3, the second part is case 4 and the last part is case 7 respectively. The first part shows the relation between the number of an EV load and DTR voltage imbalance of DTR 50, 100, 160, 250 KVA, and EQU at phase A. The maximum of an EV load are 3, 6, 10, 14, and 10 sets per DTR respectively. The second part fixes the maximum number of an EV load at phase A and increase the number of an EV load at phase B to study the DTR voltage imbalance. The graph shows, if increase the number of an EV load at the second phase, the voltage imbalance will be decreasing at the beginning. Then, the voltage imbalance will be increasing and may be higher than plug-in EV load at one phase. The maximum of an EV load are 6, 12, 20, 28, and 20 sets per DTR respectively. The last part fixes the maximum number of an EV load at phase A and B, then increase the number of an EV load at phase C to study the DTR voltage imbalance. The graph shows, if increase the number of an EV load until it equal number of all phases, the voltage imbalance will be decreased to 0%. The maximum number of EV load are 9, 18, 30, 42, and 30 sets per DTR respectively.

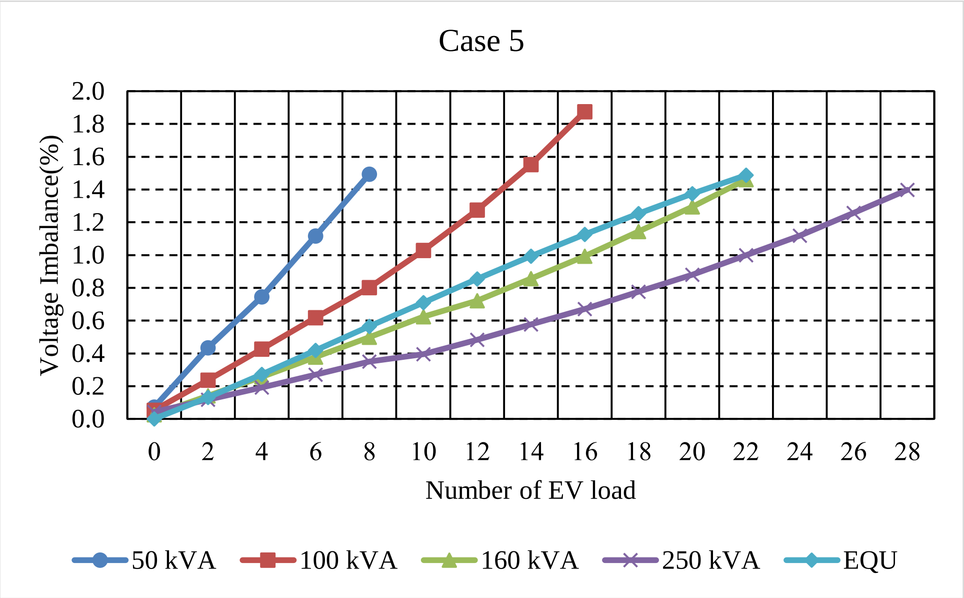

Figure 3.14 Case 5 DTR voltage imbalance

Figure 3.14 shows the relation between the number of an EV load and DTR voltage imbalance of DTR 50, 100, 160, 250 KVA, and EQU in case 5. The maximum number of an EV load are 6, 12, 20, 28, and 20 sets per DTR respectively. This simulation increases the number of an EV load at phase A and B to study the DTR voltage imbalance of an EV load per each DTR. The graph shows, if increase the number of an EV load, the voltage imbalance will be increasing.

Figure 3.15 shows the relation between the number of an EV load and DTR voltage imbalance of DTR 50, 100, 160, 250 KVA, and EQU in case 6. The maximum number of an EV load are 9, 18, 30, 42, and 30 sets per DTR respectively. This simulation fixes a number of an EV load at phase C, then increase an EV load at phase A and B. The graph shows, if increase the number of an EV load until the same number of all phases the voltage imbalance will be decreased to 0%.

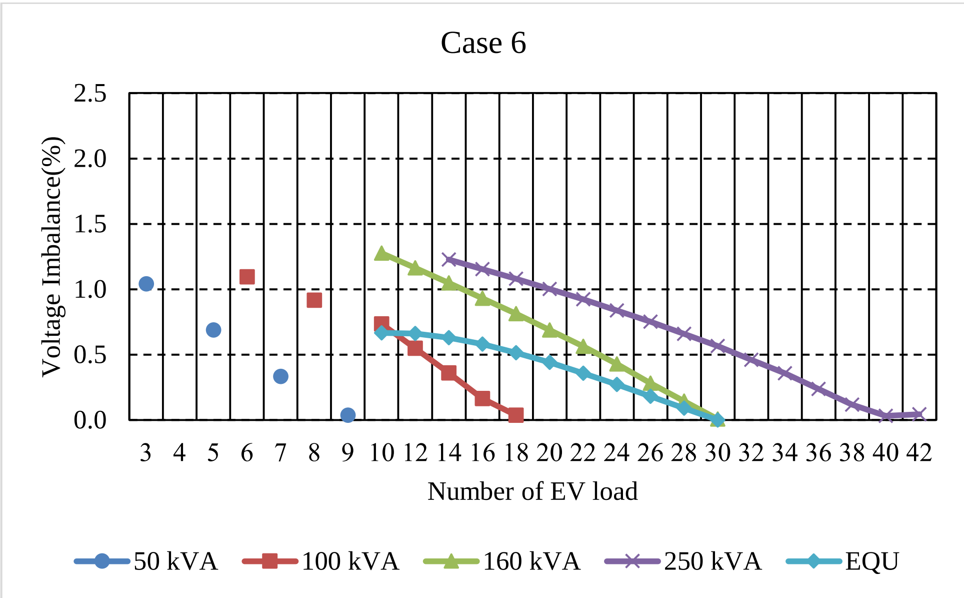

Figure 3.15 Case 6 DTR voltage imbalance

Table 3.3 shows the acceptable number of an EV load at DTR that it can use as a guideline for a utility to control the number of an EV load per phase that does not more than loading and voltage imbalance voltage impact at DTR. When there is low penetration of an EV load, a utility has to control the number of an EV load in each phase that does not more than the maximum number of an EV load per phase. When there is high penetration of an EV load, a utility has to install an Advanced Metering Infrastructure (AMI) that is working with the TEMS to control the number of an EV load to mitigate an impact and to meet the demand of a utility's DTR under control algorithm of coordinating charge.

Table 3.3 Acceptable number of an EV load at a DTR

DTR Size	Maximum No. of an EV load without Controller					
	3Ø	1Ø	1Ø+1Ø	2Ø	2Ø+1Ø	Maximum EV load /Ø
50	9	3	6	6	9	3
100	18	6	12	12	18	6
160	30	10	20	20	30	10
250	42	14	28	28	42	14

3.5 Optimization of Distribution Transformer Energy Management System

This method develops for finding an optimal schedule that maximizes the minimum final SOC (FNSOC) of all EV load at a DTR as equation (7).

Objective:

$$\max_{Schedule} \quad \min_{i=1,2,\ldots,n} \quad FNSOC_i \tag{7}$$

Where $FNSOC_i$ is the final SOC of each EV.

These optimizations are subject to:

P_{DTR} < DTR rated

Voltage imbalance ≤ 2 %

$0 \leq N_A \leq 20$

$0 \leq N_B \leq 20$

$0 \leq N_C \leq 20$

Where DTR rated is 50, 100, 160, and 250 kVA; voltage imbalance is the voltage imbalance at DTR terminal; NA, NB, NC is the number of the EV load at phase A, B, C respectively.

3.6 EV Charging Schedule Algorithm Module

In this part, we develop a charging strategy algorithm module that work with previous module. Then test the result with the DIgSILENT software.

3.6.1 Charging Strategy Algorithm Module Development

Figure 3.16 shows an EV charging schedule algorithm module, it creates a charging schedule everyday by using a statistic load curve. It is controlled by a loading and voltage imbalance module. It operation are as follows:

Step 1: EV load connect to the grid and send it SOC to the controller at arriving time.

Step 2: The controller checks the SOC of all EVs if lower than 100% it allows an EV load to charge.

Step 3: The controller checks the charging schedule overload or over voltage imbalance if it more the standard it will reduce the SOC check 0.1% and regenerate the charging schedule otherwise allow all EV loads charged as the schedule.

Step 4: Calculate the statistic of all EV loads.

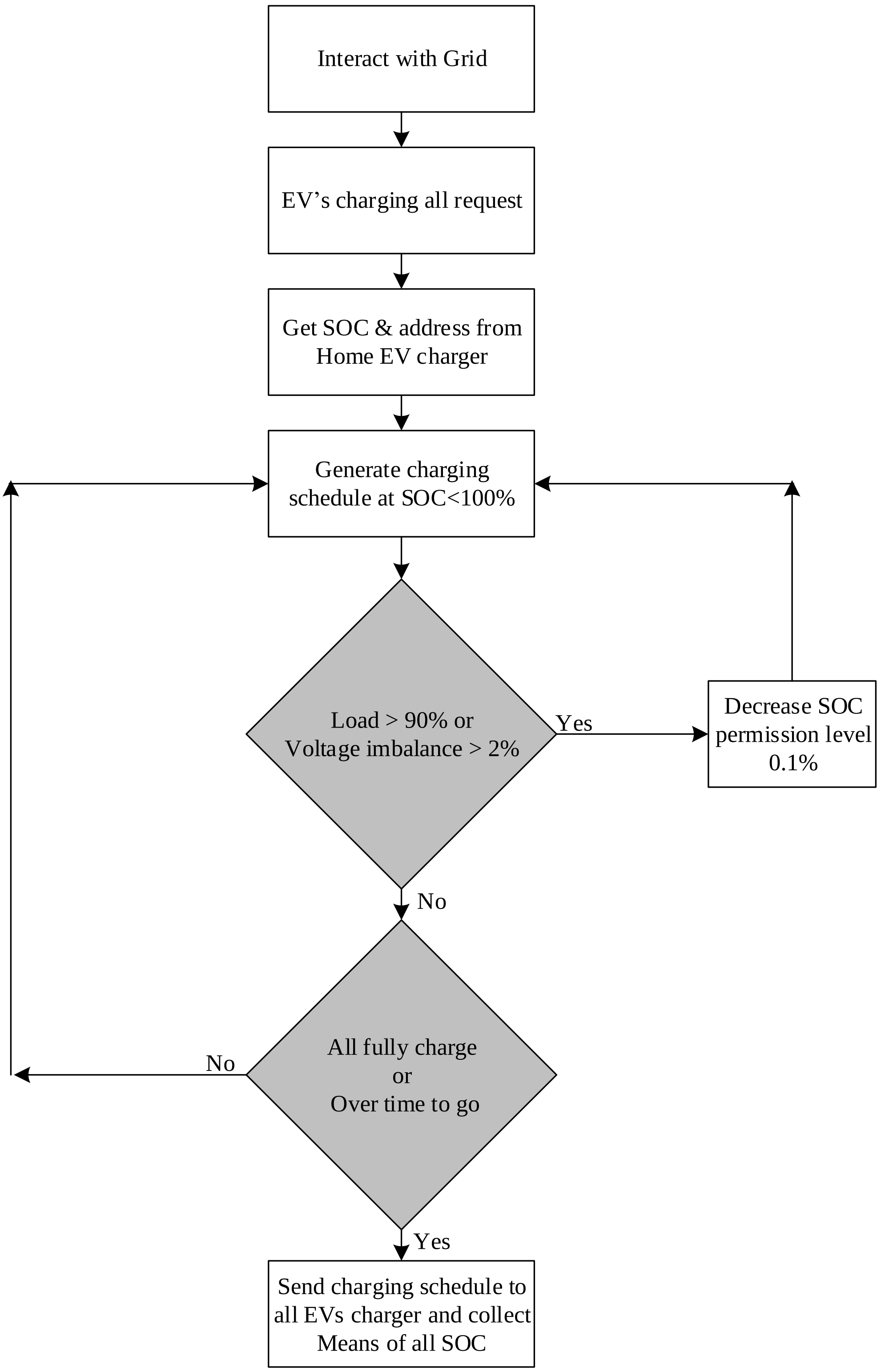

Figure 3.16 EVs charging schedule algorithm

3.6.2 Charging Strategy Algorithm Module Development Result

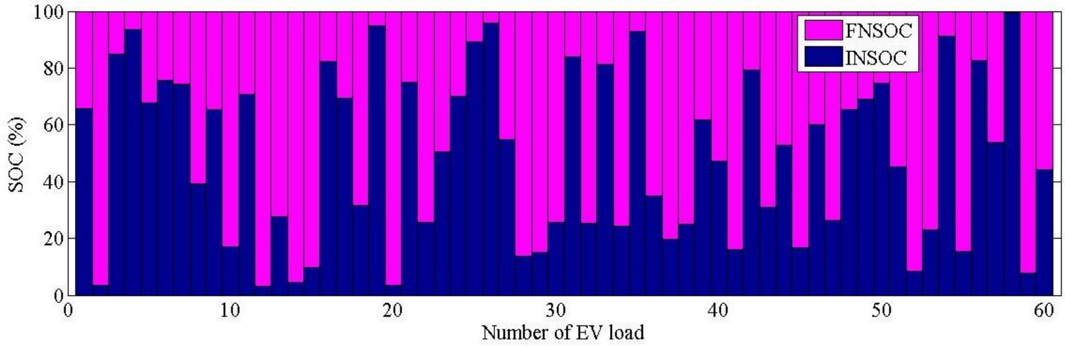

Figure 3.17 EV's battery SOC chart

Figure 3.17 shows the initial state of charge (INSOC) and the final state of charge (FOSOC) from the proposed algorithm. It can schedule an EV load to fully charge.

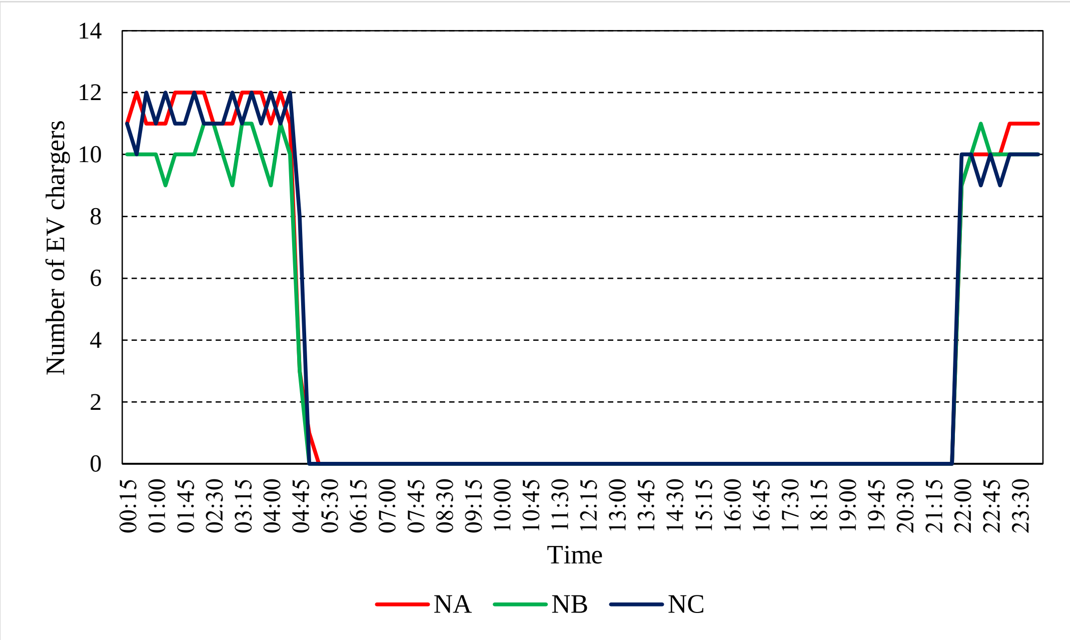

Figure 3.18 EV charging schedule

Figure 3.18 shows a number of an EV load per each phase that manage by the proposed algorithm. It controls an EV load to charge or pause that it depends on DTR loading and voltage imbalance module. It operates each 15 minutes.

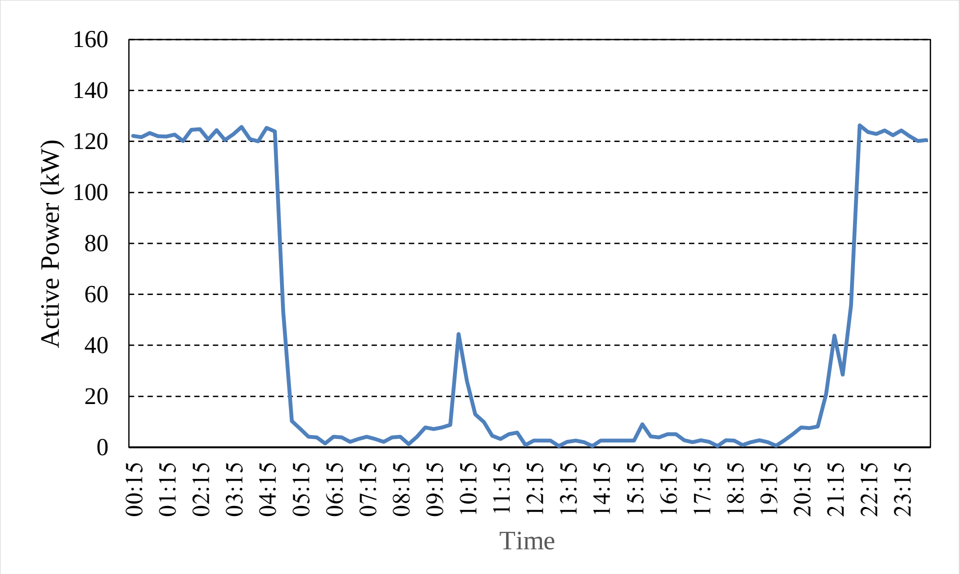

Figure 3.19 DTR loading curve with EV loads

Figure 3.19 shows a DTR's loading curve from the proposed algorithm. It maintains the DTR's loading that does not more than 160 kVA (160 kVA X 0.9 = 144 kW).

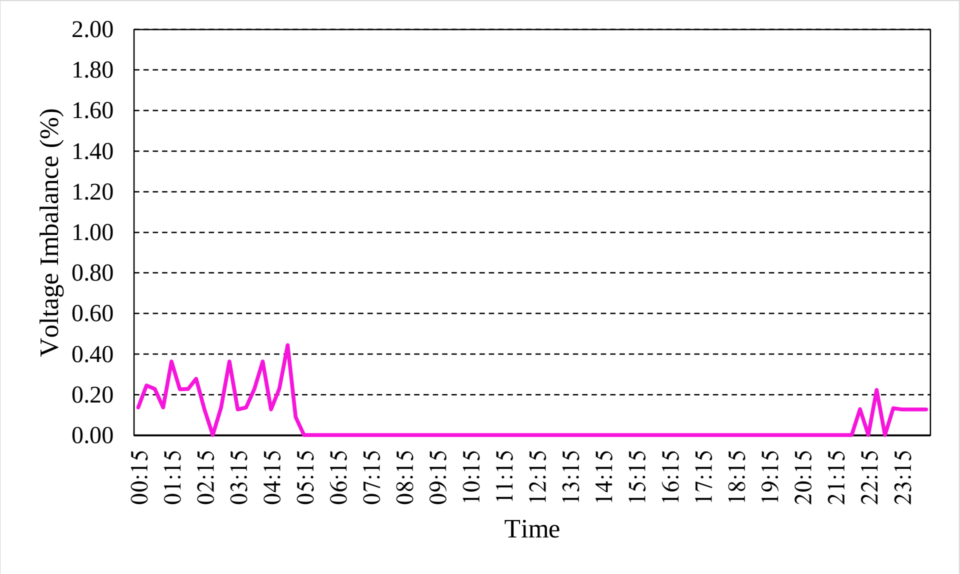

Figure 3.20 DTR voltage imbalance curve with EV loads

Figure 3.20 shows a DTR's voltage imbalance curve from the proposed algorithm. It keeps the DTR's voltage imbalance do not more than 2%.

3.7 DIgSILENT Model and DPL Script for Auto Calculation

The DIgSILENT PowerFactory software (DIgSILENT software) is a power system simulation software that the PEA uses it to study the PEA's distribution system. From Figure 3.21 we can use the DIgSILENT software for proving the result of the equivalent circuit. The easiest way of using the DIgSILENT software to simulate a system is using the DIgSILENT Programming Language (DPL) script. It can calculate and export the result to a matrix or a CSV file.

3.7.1 Model for Simulation

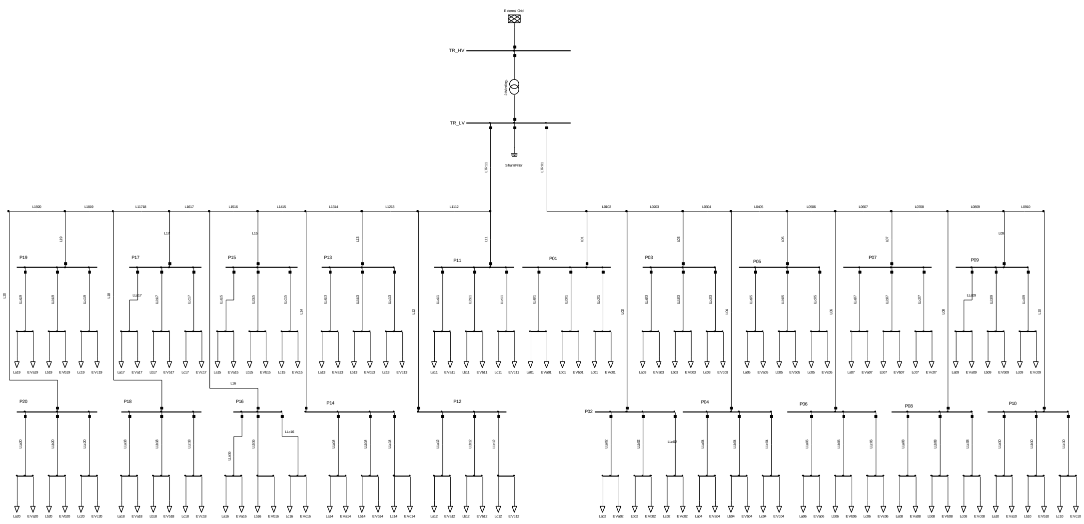

Figure 3.21 Simulation model in DIgSILENT software

The model in Figure 3.21 consists of a DTR, a LV load, a Conductor, a Bus bar, and an External Grid. In this study, we configure an element as follows:

Distribution Transformer Element (DTR)

DTR is a two winding transformer as shown in Figure 3.22, its use to step down the voltage from 22,000 volts to 400/230 volt. In this study, we use a model MT3160D from the PEA library. Setting parameter of a DTR as shown in Figure 3.23 – 3.24.

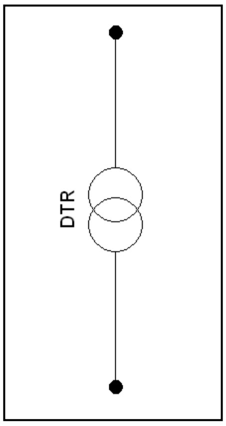

Figure 3.22 Two winding transformer element symbol

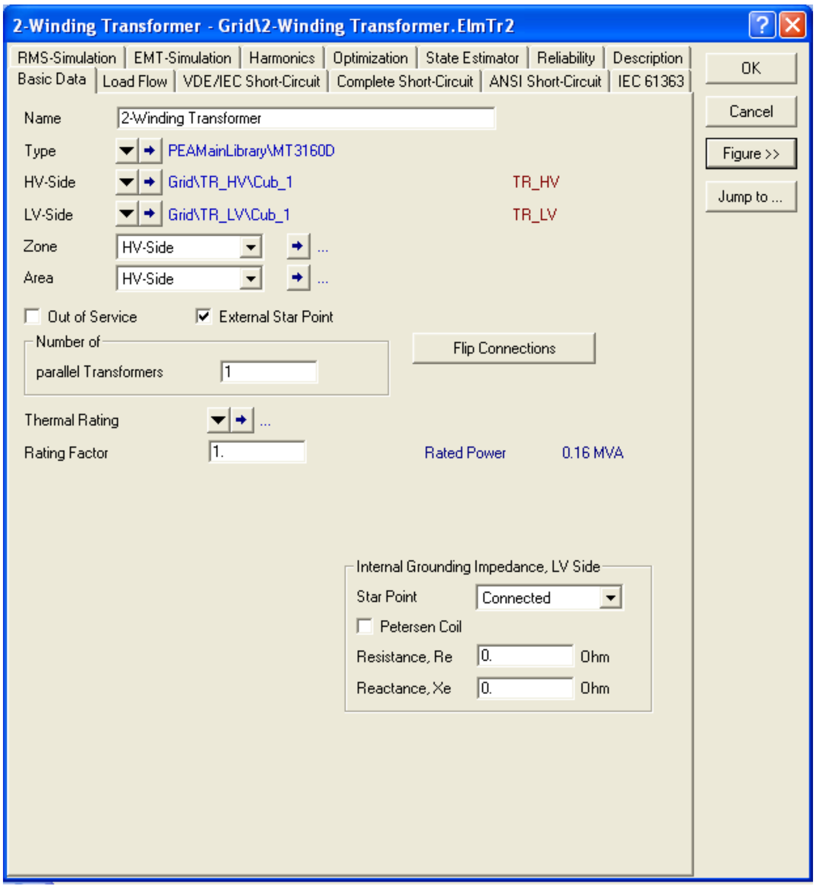

Figure 3.23 Two winding transformer element

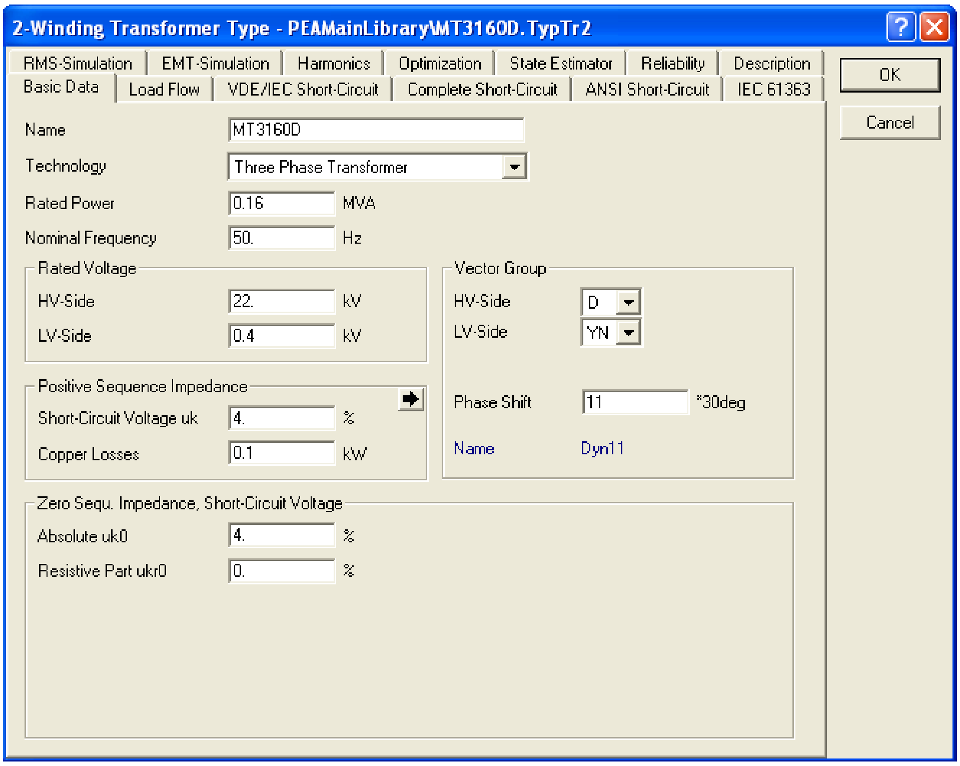

Figure 3.24 Two winding transformer configuration

LV Load Element

LV load is a load element. We use it as a base load and an EV load that it as shown in Figure 3.25. Setting parameter of a LV load for a base load and an EV load as shown in Figure 3.26 – 3.27 respectively.

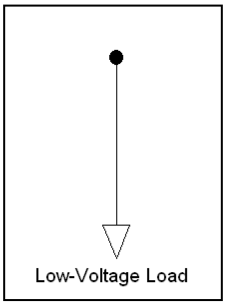

Figure 3.25 Low voltage load element symbol

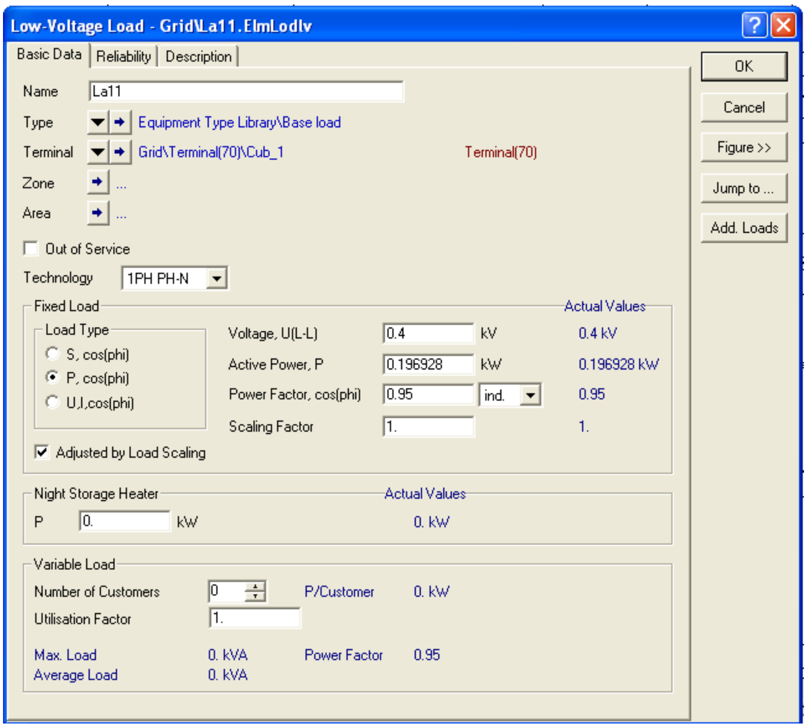

Figure 3.26 Base load configuration

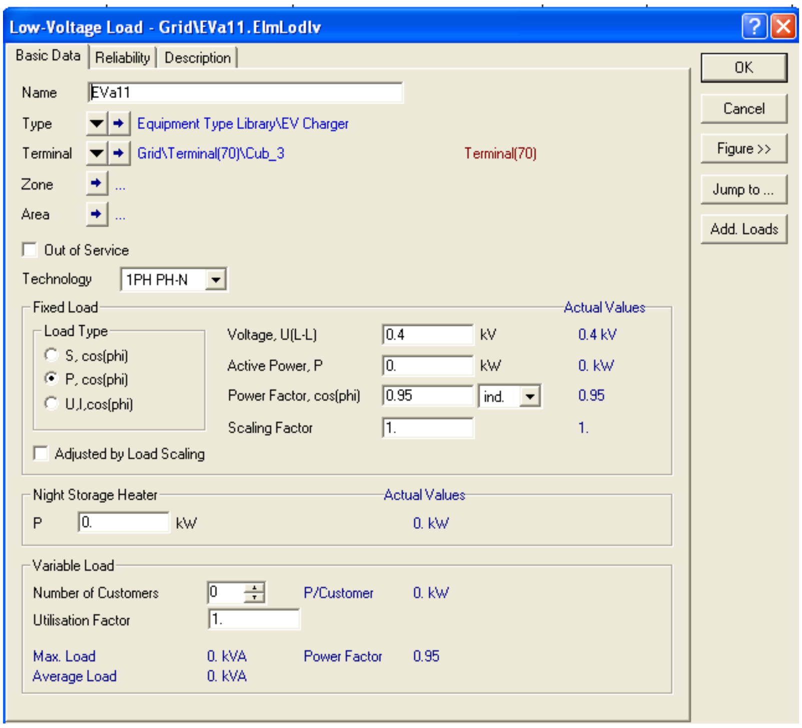

Figure 3.27 EV load configuration

Conductor Element

Conductor element in this study is a low voltage distribution conductor. UL3H95A is a three phase 95 sq.mm. aluminum conductor, it's configured as shown in Figure 3.28 - 3.29.

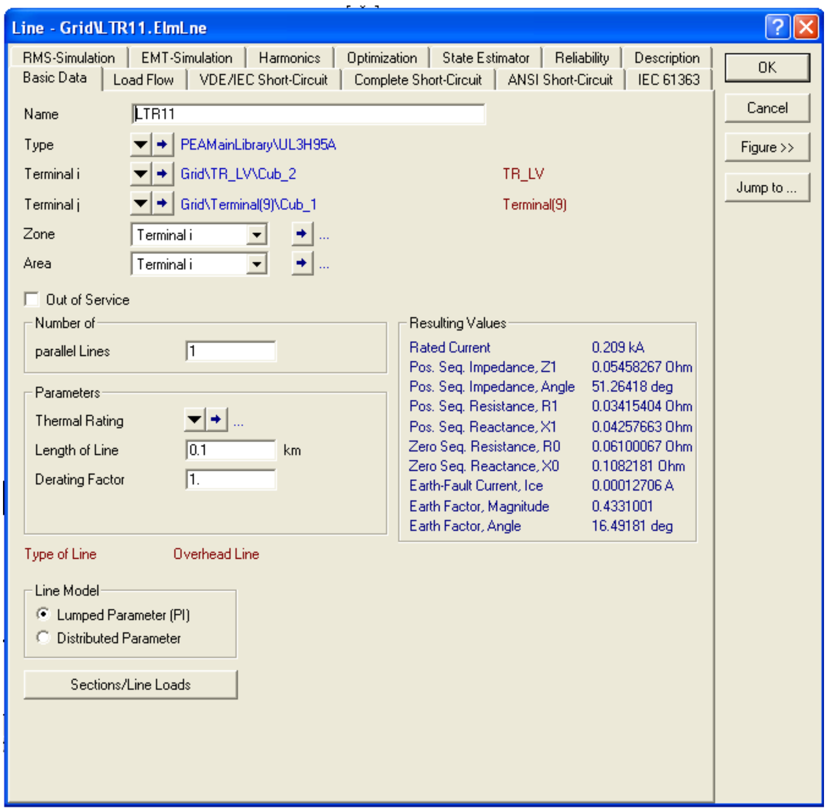

Figure 3.28 Conductor element (UL3H95A)

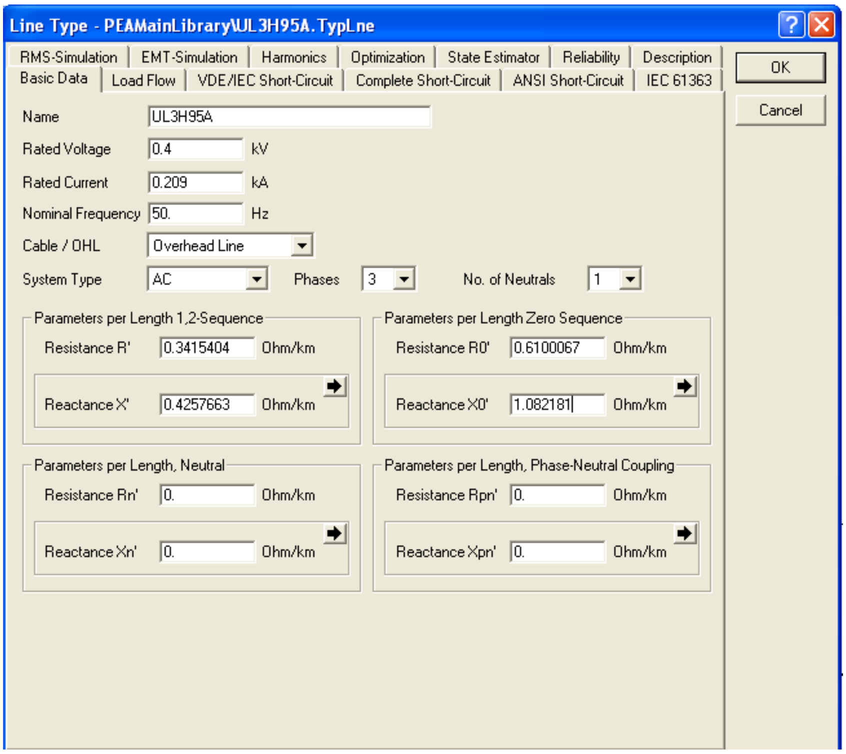

Figure 3.29 Conductor configuration (UL3H95A)

UL1H95A is a single phase 50 sq.mm. aluminum conductor, it's configured as shown in Figure 3.30 - 3.31.

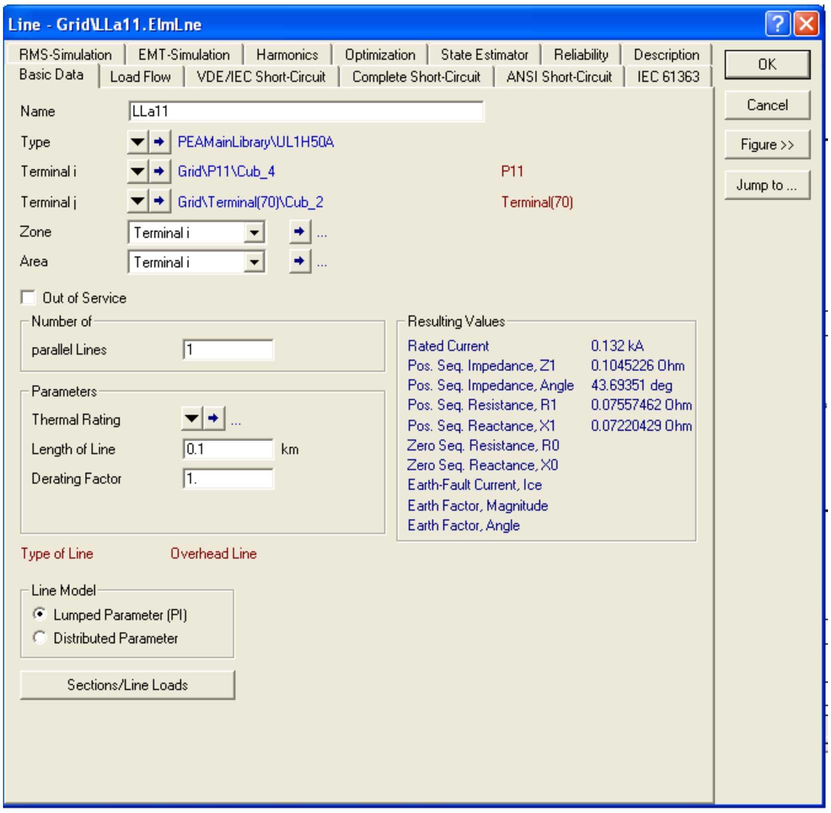

Figure 3.30 Conductor element (UL1H50A)

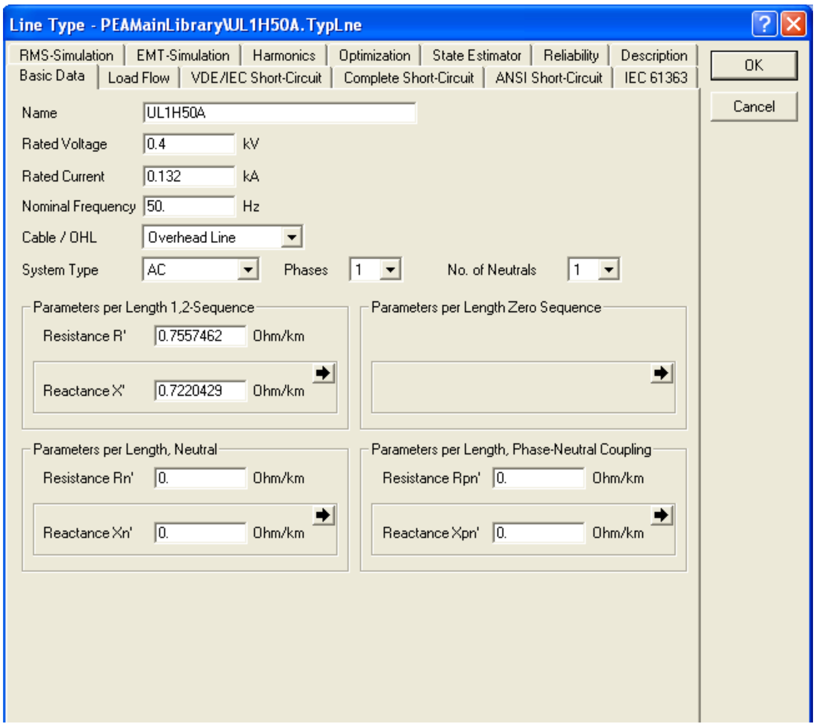

Figure 3.31 Conductor configuration (UL1H50A)

3.7.2 Flowchart of DPL Script

We use a DPL script with a simulation model, it can input value of a base load and an EV load via a matrix. Then it can change time step and collect the output data into matrixes. In this study, the DPL script flow chart as shown in Figure 3.32. It operation are as follows:

Step 1: Input a base load and an EV load into matrixes.

Step 2: Check number of all bus.

Step 3: Set dimension of matrixes = 96 X a number of a buses from step 2. 96 is coming from 15 minutes per hours X 24 hours.

Step 4: Load value of a base load and an EV load into a model.

Step 5: Run a load flow function.

Step 6: Get value of positive, negative, and zero sequence voltage, and power into matrixes.

Step 7: Increase time step.

Step 8: If the time step less than 96 go to step 4, else end to simulate.

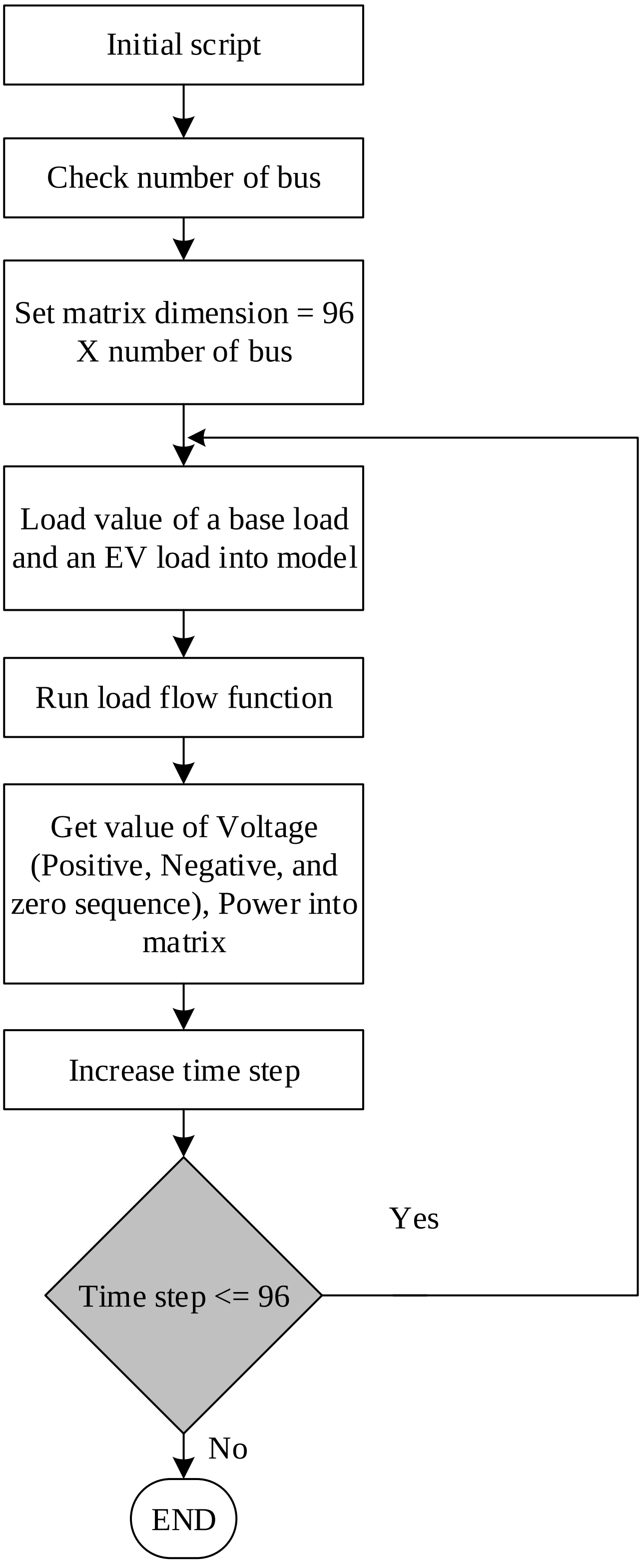

Figure 3.32 Simulation DPL script flowchart

3.7.3 DPL Script Simulation Result

In this study, we use the model as shown in Figure 3.21 with the DIgSILENT software and a DPL script for proving the result from the proposed algorithm. The result of DTR's loading and Voltage imbalance from a DPL script as shown in Figure 3.33 - 3.34 respectively.

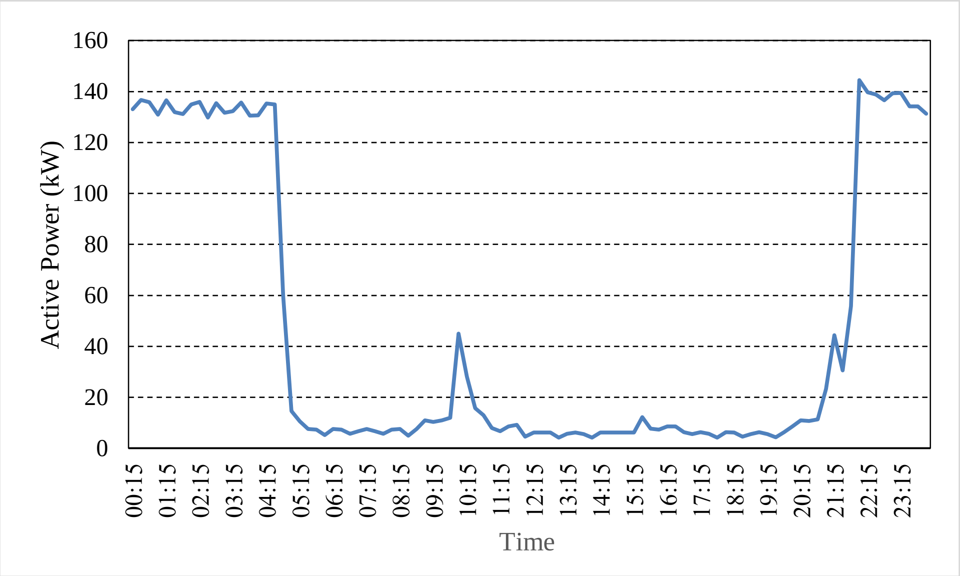

Figure 3.33 DTR loading curve with EV loads

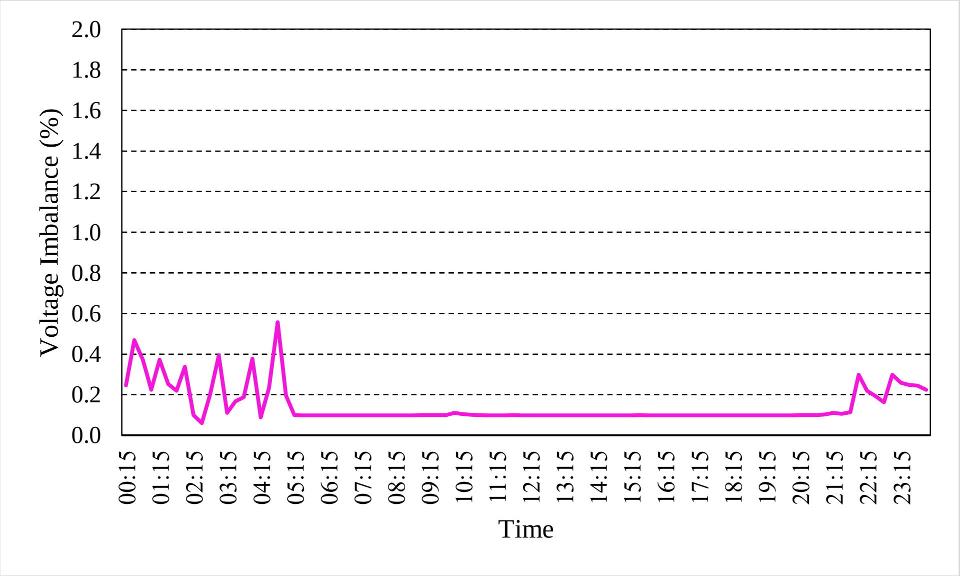

Figure 3.34 DTR voltage imbalance curve with EV loads

3.8 Model Development Discussion

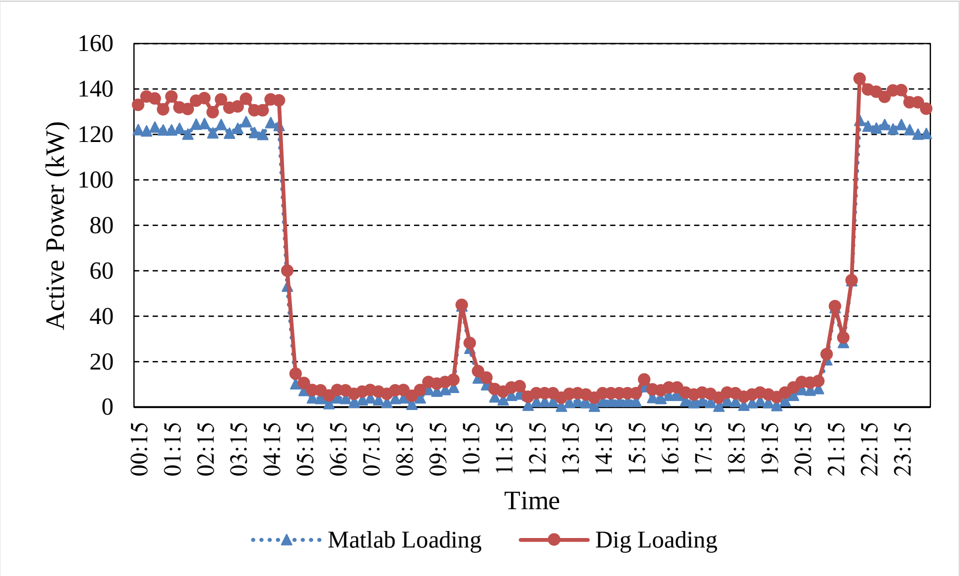

Figure 3.35 Loading result compares between the MATLAB and the DIgSILENT software

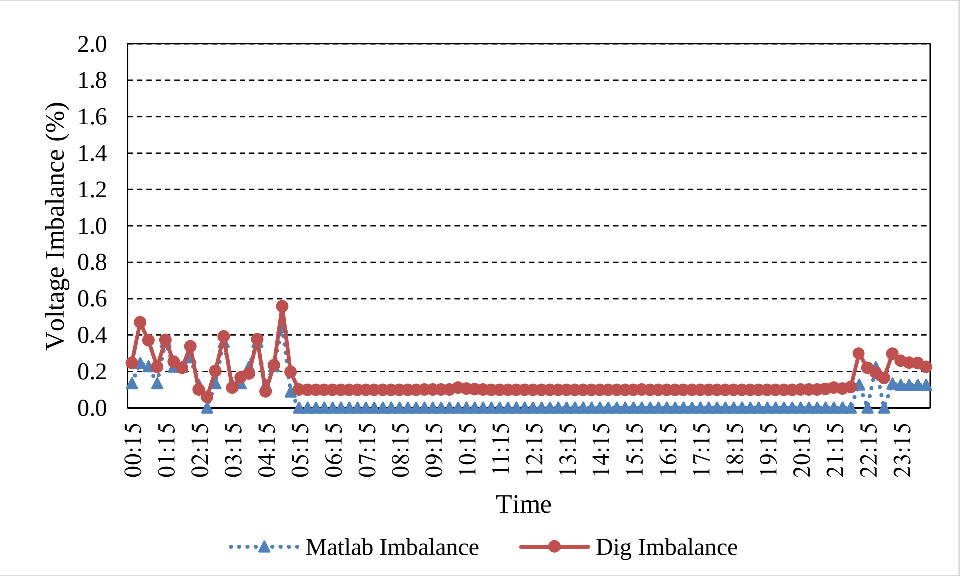

Figure 3.36 Voltage imbalance result compares between the MATLAB and the DIgSILENT software

Figure 3.35 and 3.36 show the loading and voltage imbalance result that it compare between the result from the MATLAB and the DIgSILENT software. Figure 3.35

shows that it nearly match for the loading result. Figure 3.36 shows the results from the MATLAB lower than the DIgSILENT software. The result from the MATLAB and the DIgSILENT software is the same trend. The proposed method can apply to use in the distribution transformer management system (TEMS).

3.9 Key Performance Indicator Calculation

In this part, we present Key Performance Indicator of customers and utility. It can evaluate the performance of TEMS.

3.9.1 Customer Key Performance Indicator (Customer KPI)

Customer KPI is customer satisfaction that we indicate by FNSOC shown in equation (8) and (9).

$$\% \text{ FNSOC} < 80\%, \quad \text{Customer KPI} = 0\ \% \tag{8}$$

$$\% \text{ FNSOC} \geq 80\%, \quad \text{Customer KPI} = \%\ \text{FNSOC} \tag{9}$$

3.9.2 Utility Key Performance Indicator (Utility KPI)

We use Utilization Factor (UF) of a DTR as Utility KPI shown in equation (10) and (11).

$$\% \text{ UF} \leq 90\%, \quad Utility\ KPI = \frac{100}{90}\,(UF) \tag{10}$$

$$90\% > \% \text{ UF} \leq 150\%, \quad Utility\ KPI = -\frac{100}{60}\,(UF - 90) + 100 \tag{11}$$

Chapter 4
Simulation Results and Discussion

In this chapter we investigate scenarios to test the proposed algorithm. Then discuss the result of investigating scenarios. First, we investigate scenarios to study impacts with DTR. Then, we simulate the proposed algorithm in different scenarios. Finally, we discuss the results of the proposed algorithm.

4.1 Investigated Scenarios

We investigate scenarios to study a behavior of a low voltage distribution grid at a DTR with/without an EV load and with/without a control algorithm as shown in Table 4.1. The SOC of an EV battery is normal random. Plugin time in scenario 3 - 7 is the exponential distribution from 10 - 12 p.m. The investigate scenarios are focus on the demand side (an EV load) and supply side (a DTR). Where there are the scenario 3 and 4, the demand is less than the supply but the demand is greater than the supply in case of the scenario 6 and 7. The scenario 5, the demand is nearly equal to the supply.

Scenario 1: Without an EV load and without a control algorithm (base scenario)

Scenario 2: With 10 EV load/phase, but without a control algorithm all plugs in at 6 p.m.

Scenario 3: With 10 EV load/phase and a control algorithm, random SOC, all EV load starts to charge at 10 p.m. and unplug at 6 a.m.

Scenario 4: With 20 EV load/phase and a control algorithm, random SOC, all EV load starts to charge at 10 p.m. and unplug at 6 a.m.

Scenario 5: With 25 EV load/phase and a control algorithm, random SOC, all EV load starts to charge at 10 p.m. and unplug at 6 a.m.

Scenario 6: With 30 EV load/phase and a control algorithm, random SOC, all EV load starts to charge at 10 p.m. and unplug at 6 a.m.

Scenario 7: With 35 EV load/phase and a control algorithm, random SOC, all EV load starts to charge at 10 p.m. and unplug at 6 a.m.

Table 4.1 Investigate scenarios of the study

Scenarios	Number of EV load / Phase	SOC	Control algorithm	Plug in time	Unplug time
1	0	-	-	-	-
2	10	Normal random	No	6 p.m.	6 a.m.
3	10	Normal random	Yes	Exponentially distribute from 10 - 12 p.m.	6 a.m.
4	20	Normal random	Yes	Exponentially distribute from 10 - 12 p.m.	6 a.m.
5	25	Normal random	Yes	Exponentially distribute from 10 - 12 p.m.	6 a.m.
6	30	Normal random	Yes	Exponentially distribute from 10 - 12 p.m.	6 a.m.
7	35	Normal random	Yes	Exponentially distribute from 10 - 12 p.m.	6 a.m.

4.2 Simulation Results

The result of the investigating scenarios using the proposed algorithm is as follows.

Scenario 1: Without an EV load and without a control algorithm (base scenario)

Figure 4.1 shows a DTR's loading curve with a base load. The peak load is at 9.45 p.m. Figure 4.2 shows a DTR's voltage imbalance with a base load. It balances distribution along a distribution grid.

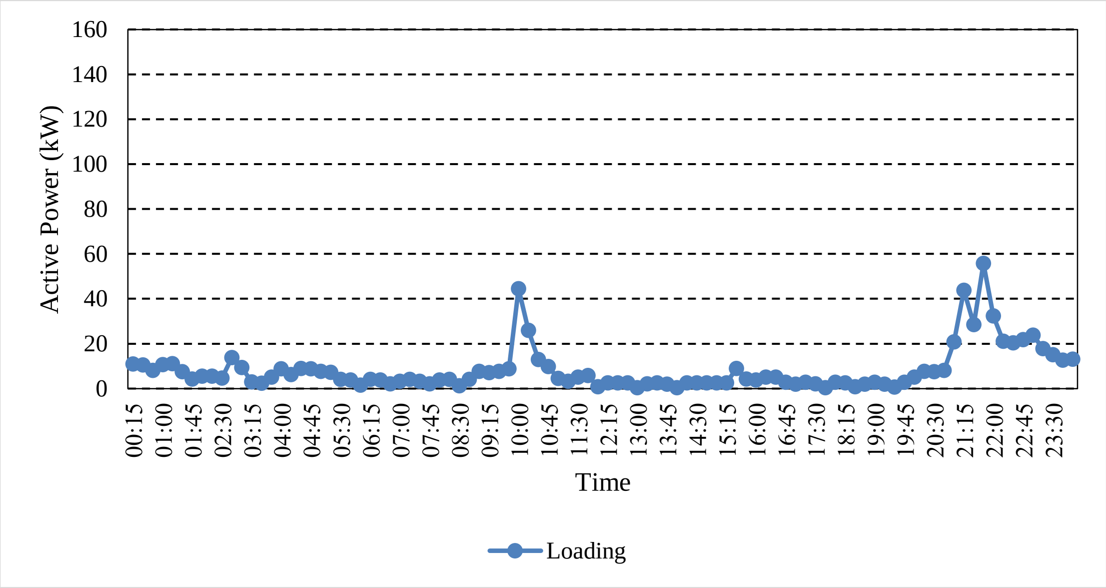

Figure 4.1 Scenario 1 DTR's loading curve

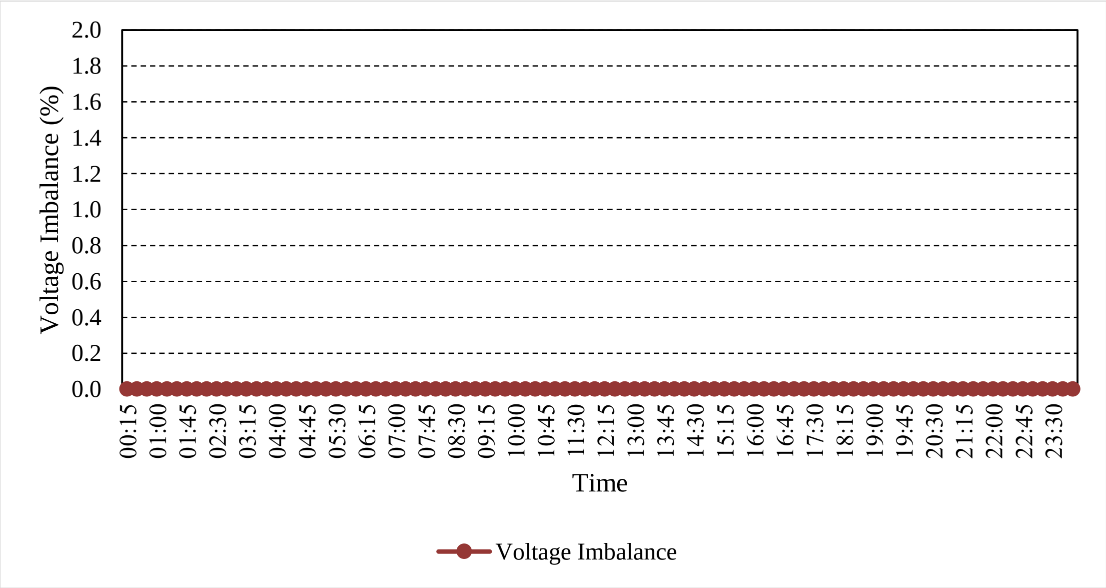

Figure 4.2 Scenario 1 DTR's voltage imbalance curve

Scenario 2: With 10 EV load/phase, but without a control algorithm all plugs in at 6 p.m. Figure 4.3 shows EV loads charging schedule without a TEMS that they all plug in at 6 p.m. and fully charge at 1 a.m. Figure 4.4 shows a DTR's loading curve with 10 EV loads/phase, without a TEMS. It does not overload at the peak time. Figure 4.5 shows a DTR's voltage imbalance not more than the standard. The statistics of an EV load shown in Table 4.2.

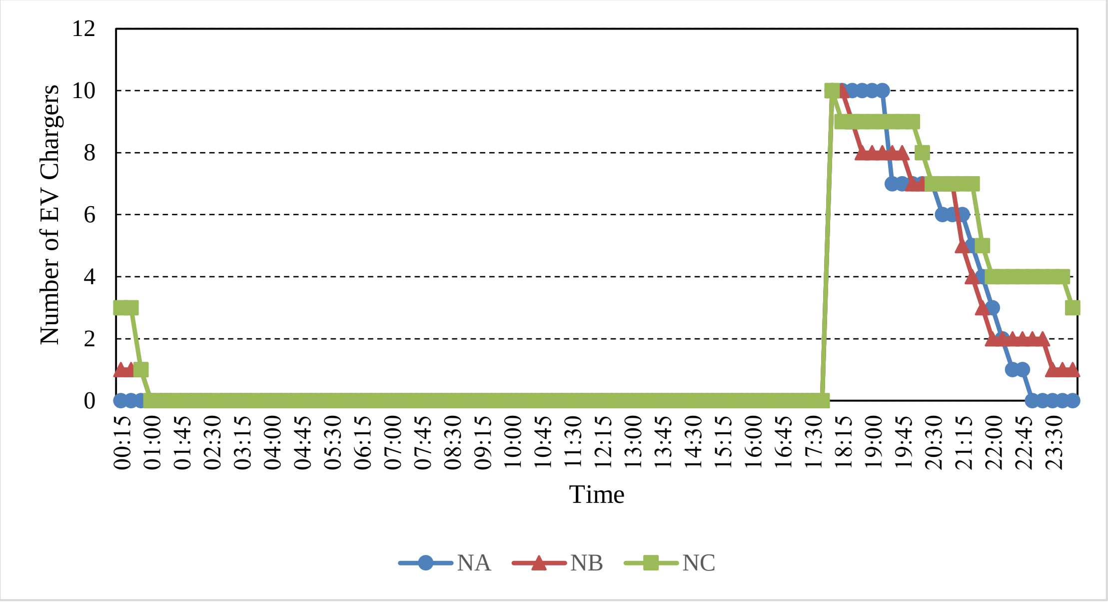

Figure 4.3 Scenario 2 EV loads charging schedule

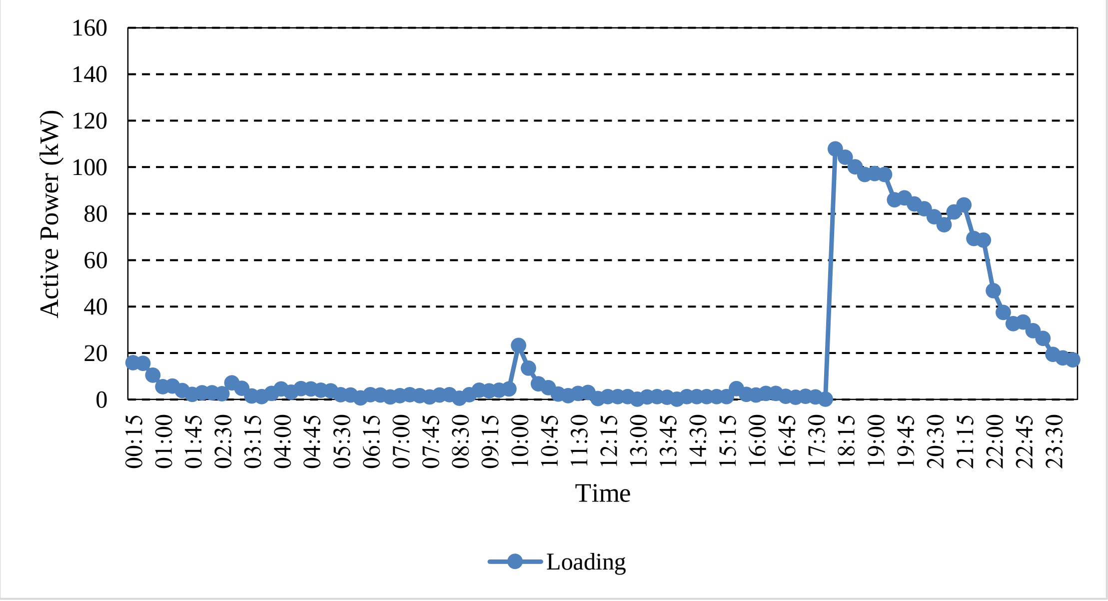

Figure 4.4 Scenario 2 DTR's loading curve

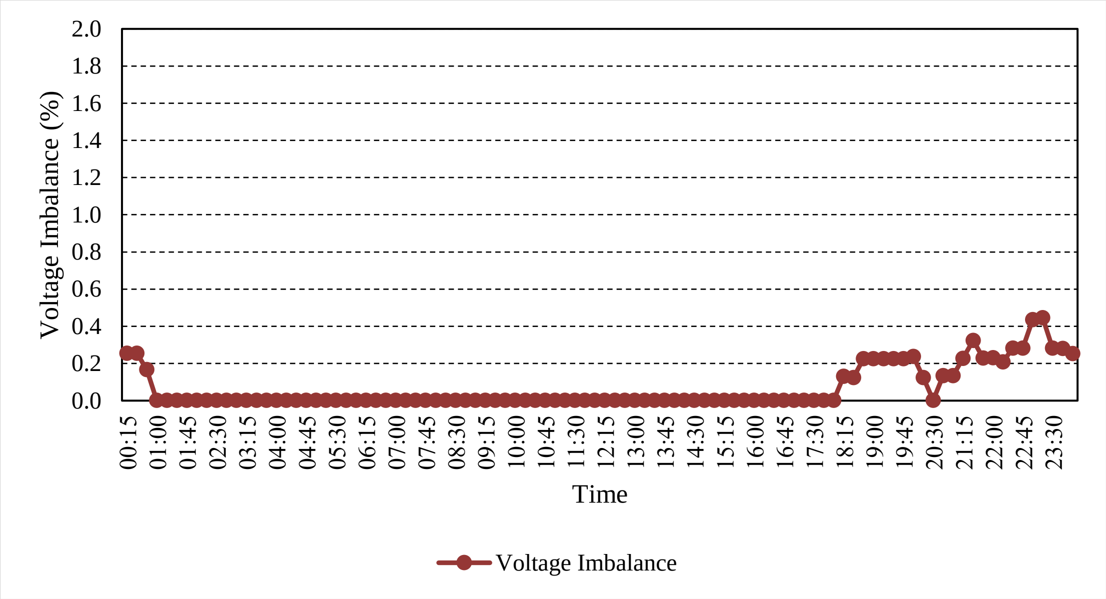

Figure 4.5 Scenario 2 DTR's voltage imbalance curve

Table 4.2 Scenario 2 EV load result

Description	Value	Unit
Number of EV load	10	Set/Phase
TEMS	Without	
Plug in time	6 p.m.	
Unplug time	Fully charge	
Minimum value of FNSOC	100	%
Mean of INSOC	47.99	%
Mean of FNSOC	100	%
Customer KPI	100	%
Utility KPI	9.90	%

Scenario 3: With 10 EV load/phase and a control algorithm, random SOC, all EV load starts to charge at 10 p.m. and unplug at 6 a.m.

Figure 4.6 shows EV loads charging schedule with a TEMS that they exponentially distribute to charge from 10 - 12 p.m. and unplug at 6 a.m. Figure 4.7 shows a DTR's loading curve with 10 EV loads/phase and a TEMS that it does not overload at all time. Figure 4.8 shows a DTR's voltage imbalance not more than the standard. Figure 4.9 shows EV's battery SOC chart that a DTR with TEMS can cover all EV load and can all fully charge at 6 a.m. The statistics of Scenario 3 shown in Table 4.3.

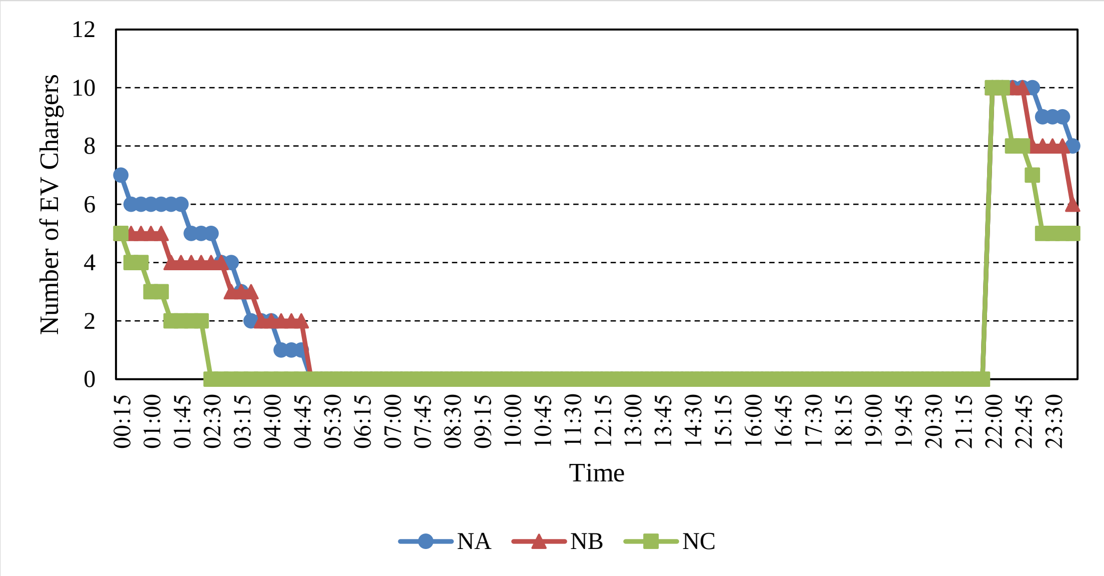

Figure 4.6 Scenario 3 EV loads charging schedule

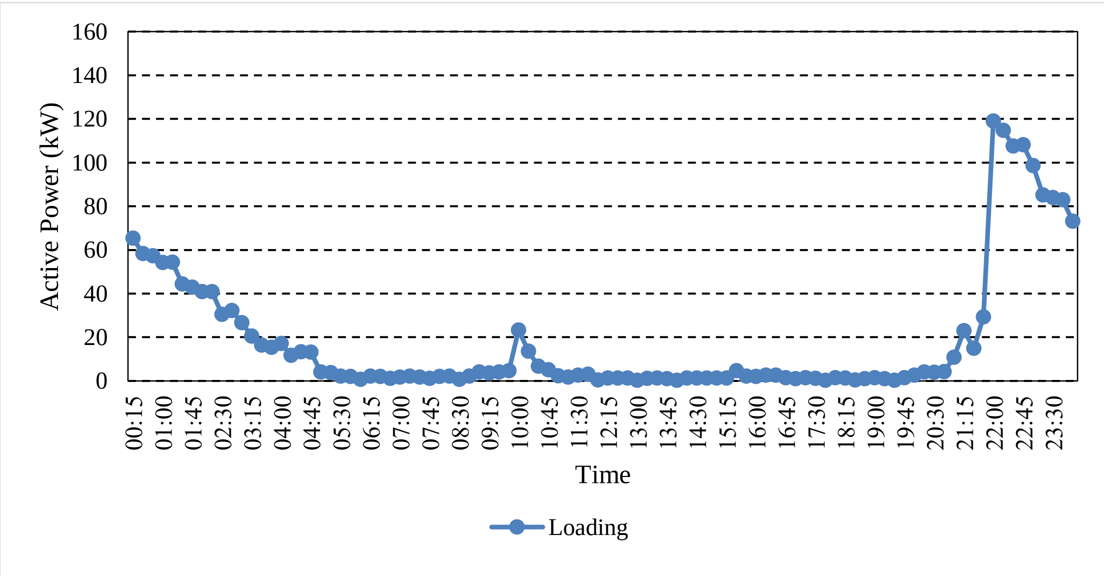

Figure 4.7 Scenario 3 DTR's loading curve

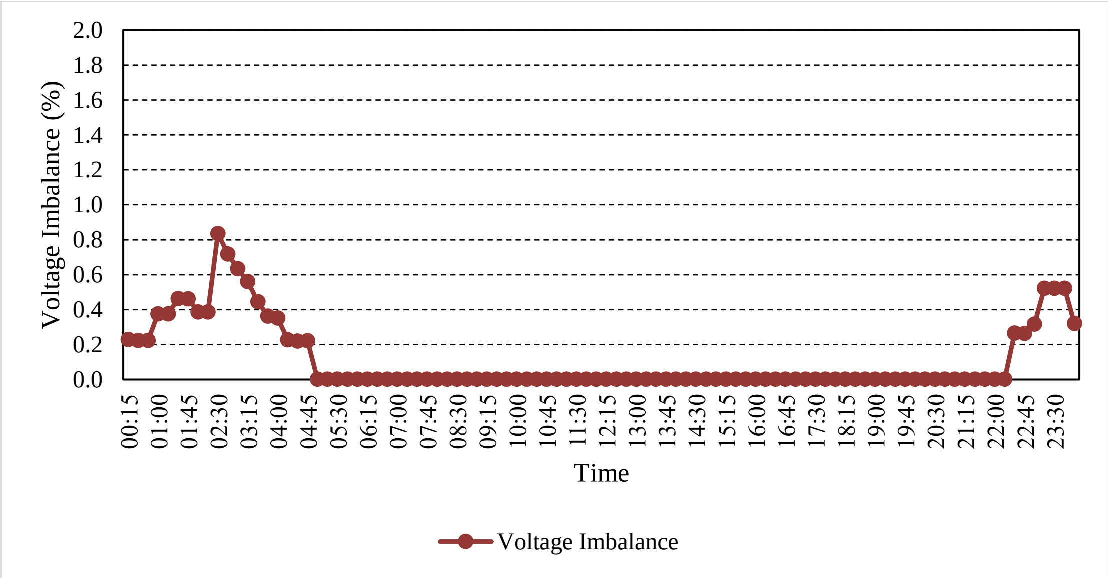

Figure 4.8 Scenario 3 DTR's voltage imbalance curve

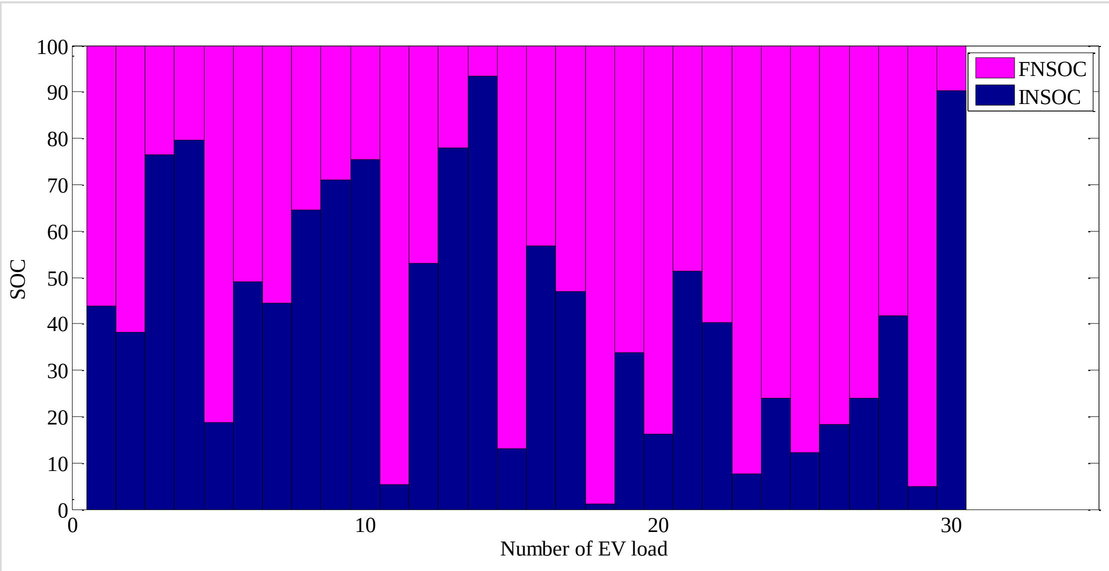

Figure 4.9 Scenario 3 EV's battery SOC chart

Table 4.3 Scenario 3 EV load result

Description	Value	Unit
Number of EV load	10	Set/Phase
TEMS	With	
Plug in time	Exponentially distribute from 10 - 12 p.m.	
Unplug time	6 a.m.	
Minimum value of FNSOC	100	%
Mean of INSOC	48.70	%
Mean of FNSOC	100	%
Customer KPI	100	%
Utility KPI	35.60	%

Scenario 4: With 20 EV load/phase and a control algorithm, random SOC, all EV load starts to charge at 10 p.m. and unplug at 6 a.m.

Figure 4.10 shows EV loads charging schedule with a TEMS that they exponentially distribute to charge from 10 - 12 p.m. and unplug at 6 a.m. Figure 4.11 shows a DTR's loading curve with 20 EV loads/phase, with a TEMS. It does not overload at all time. Figure 4.12 shows a DTR's voltage imbalance not more than the standard. Figure 4.13 shows EV's battery SOC chart that a DTR with TEMS can cover all EV load and can almost fully charge at 6 a.m. Means of final stage of charge is 98.37. The statistics of Scenario 4 shown in Table 4.4.

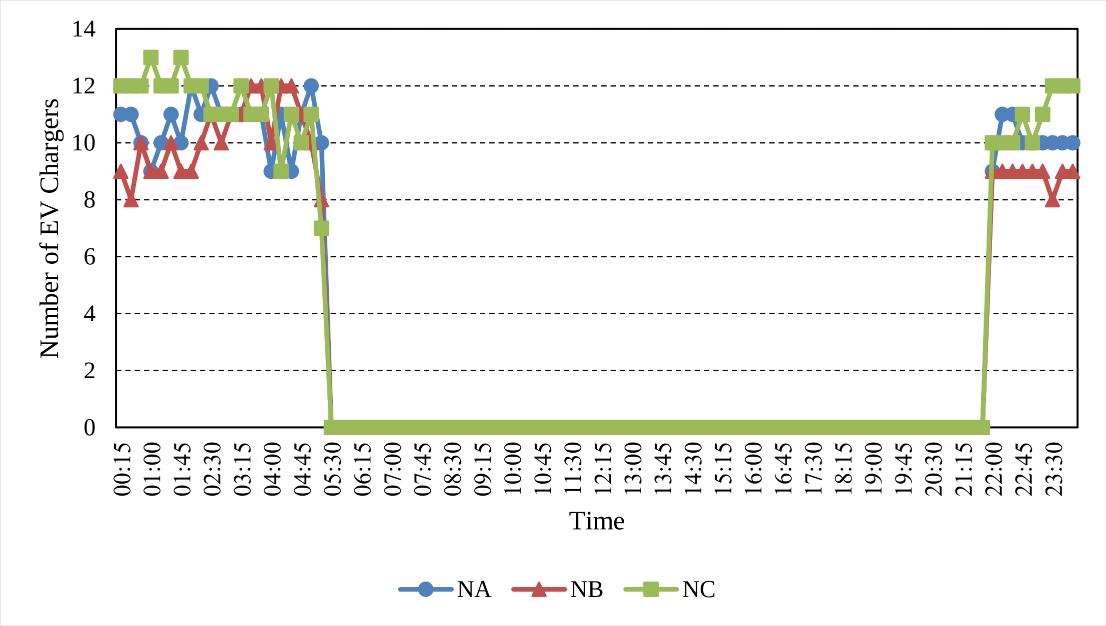

Figure 4.10 Scenario 4 EV loads charging schedule

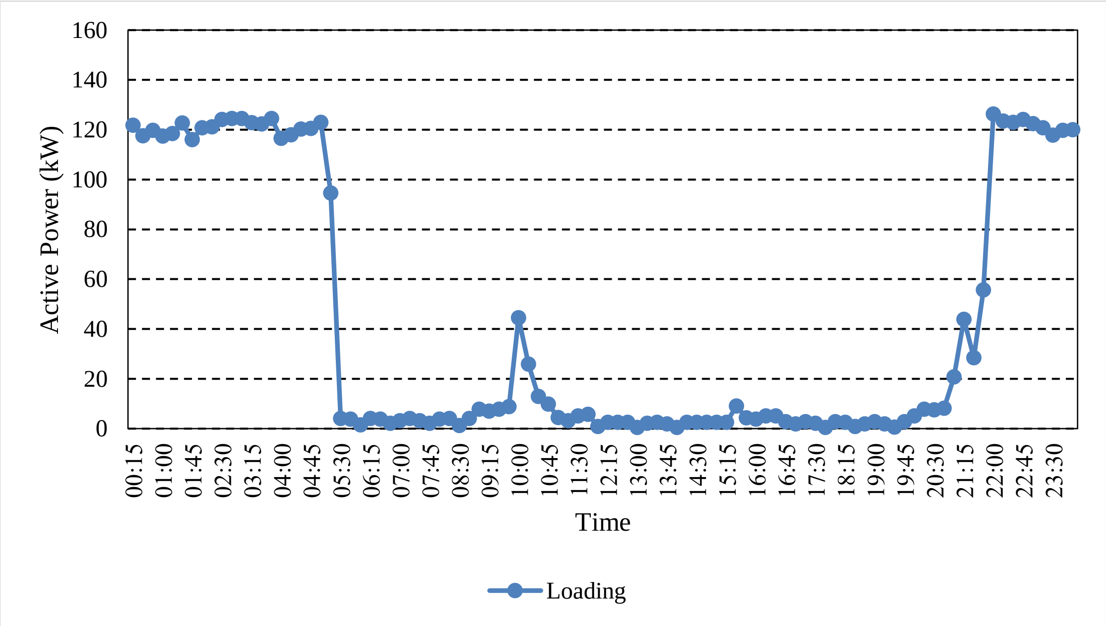

Figure 4.11 Scenario 4 DTR’s loading curve

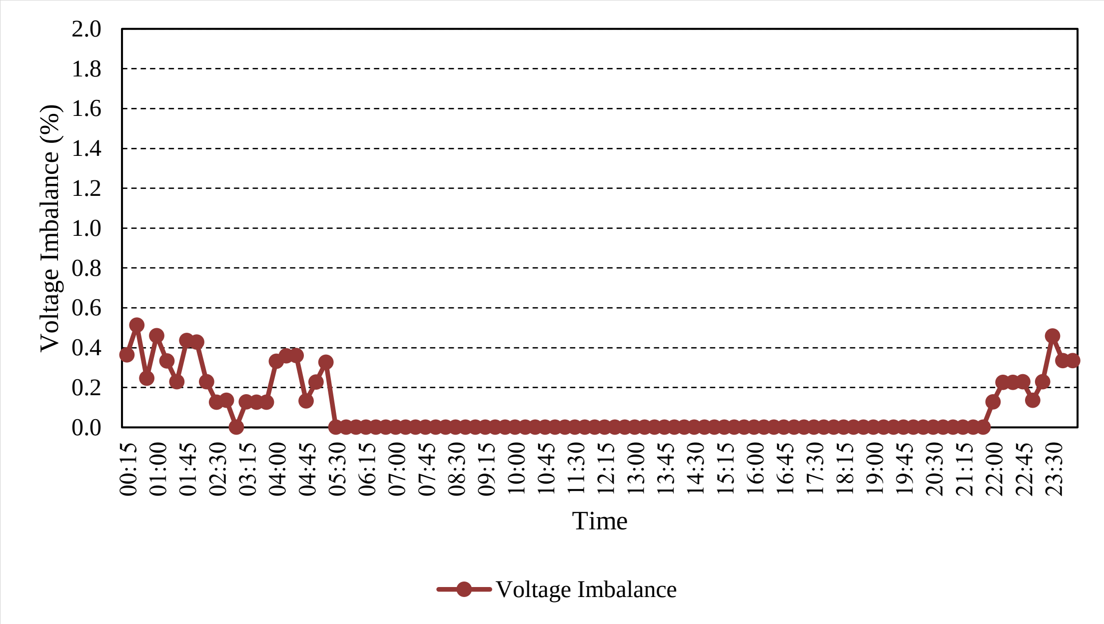

Figure 4.12 Scenario 4 DTR’s voltage imbalance curve

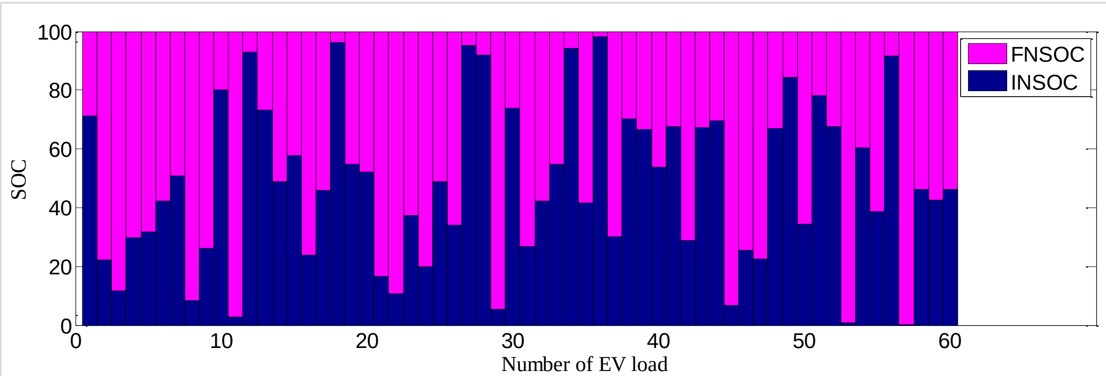

Figure 4.13 Scenario 4 EV’s battery SOC chart

Table 4.4 Scenario 4 EV load result

Description	Value	Unit
Number of EV load	20	Set/Phase
TEMS	With	
Plug in time	Exponentially distribute from 10 - 12 p.m.	
Unplug time	6 a.m.	
Minimum value of FNSOC	97.64	%
Mean of INSOC	50.07	%
Mean of FNSOC	98.37	%
Customer KPI	99.99	%
Utility KPI	68.95	%

Scenario 5: With 25 EV load/phase and a control algorithm, random SOC, all EV load starts to charge at 10 p.m. and unplug at 6 a.m.

Figure 4.14 shows EV loads charging schedule with a TEMS that they exponentially distribute to charge from 10 - 12 p.m. and unplug at 6 a.m. Figure 4.15 shows a DTR's loading curve with 25 EV loads/phase, with a TEMS. It does not overload at all time. Figure 4.16 shows a DTR's voltage imbalance not more than the standard. Figure 4.17 shows EV's battery SOC chart that a DTR with TEMS can cover EV load and can almost fully charge at 6 a.m. Means of final stage of charge is 94.27%. The statistics of Scenario 5 shown in Table 4.5.

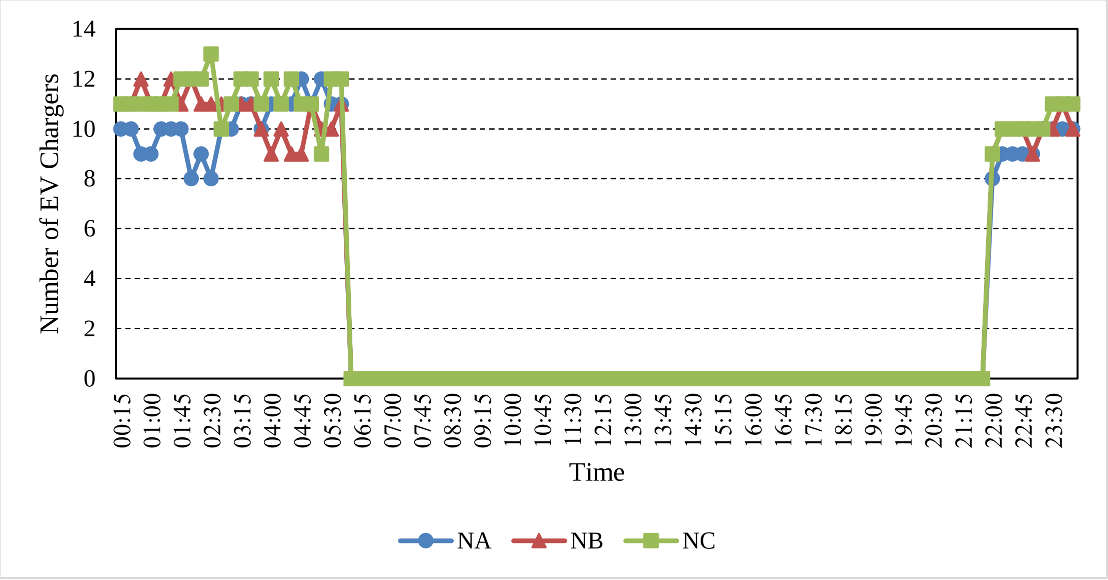

Figure 4.14 Scenario 5 EV loads charging schedule

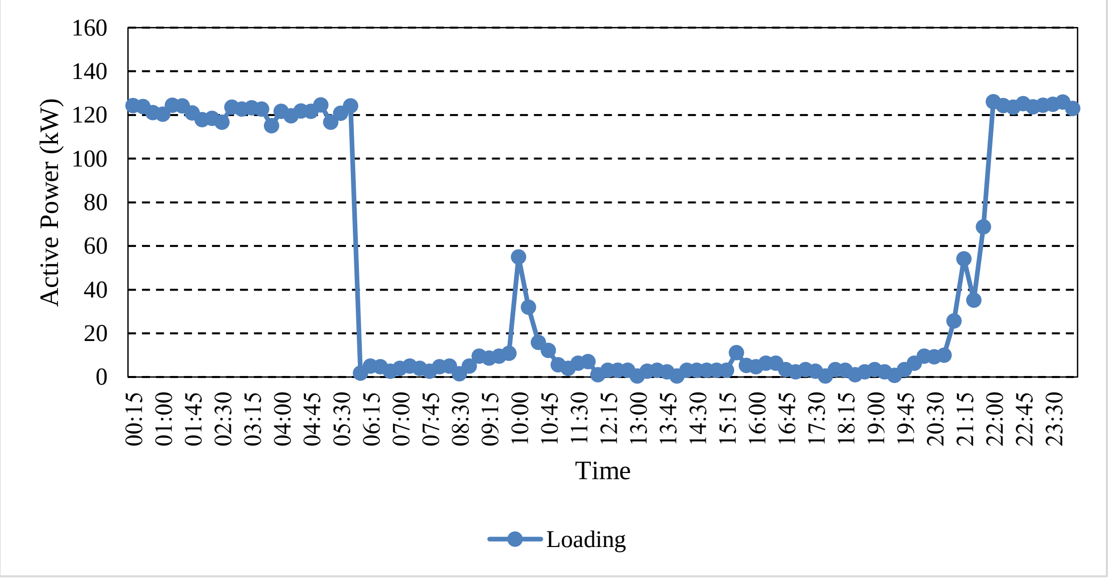

Figure 4.15 Scenario 5 DTR’s loading curve

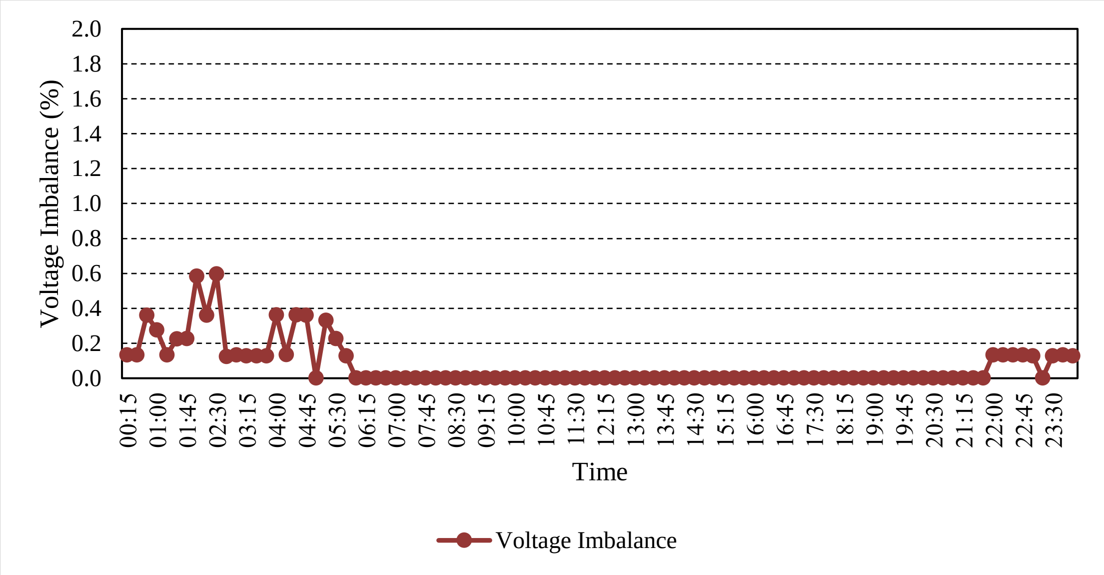

Figure 4.16 Scenario 5 DTR's voltage imbalance curve

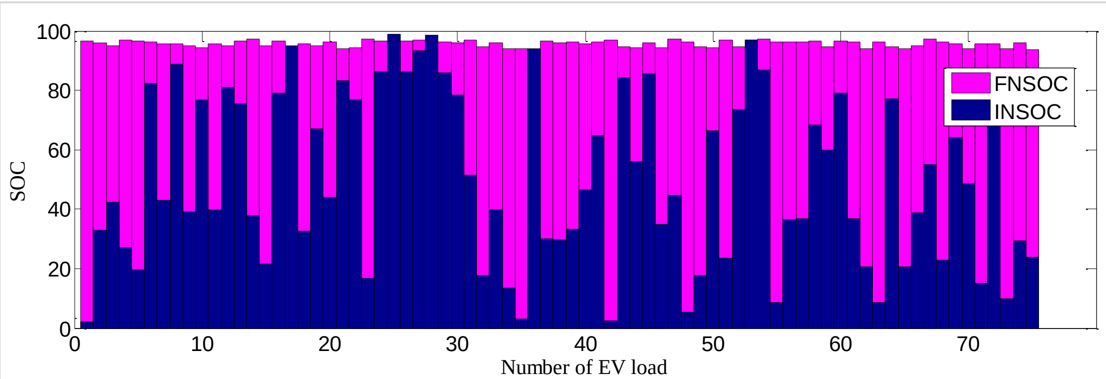

Figure 4.17 Scenario 5 EV's battery SOC chart

Table 4.5 Scenario 5 EV load result

Description	Value	Unit
Number of EV load	25	Set/Phase
TEMS	With	
Plug in time	Exponentially distribute from 10 - 12 p.m.	
Unplug time	6 a.m.	
Minimum value of FNSOC	79.83	%
Mean of INSOC	49.57	%
Mean of FNSOC	94.27	%
Customer KPI	93.95	%
Utility KPI	75.94	%

Scenario 6: With 30 EV load/phase and a control algorithm, random SOC, all EV load starts to charge at 10 p.m. and unplug at 6 a.m.

Figure 4.18 shows EV loads charging schedule with a TEMS that they exponentially distribute to charge from 10 - 12 p.m. and unplug at 6 a.m. Figure 4.19 shows a DTR's loading curve with 30 EV loads/phase, with a TEMS. It does not overload at all time. Figure 4.20 shows a DTR's voltage imbalance not more than the standard. Figure 4.21 shows EV's battery SOC chart that a DTR with TEMS can cover EV load but cannot all fully charge at 6 p.m. Means of final stage of charge is 84.91%. The statistics of Scenario 5 shown in Table 4.6.

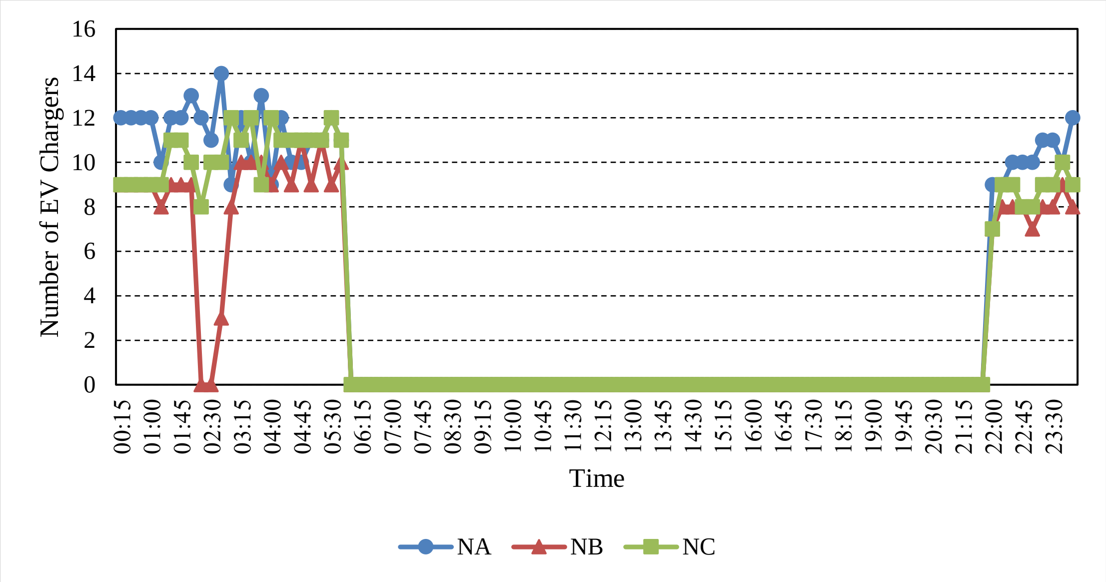

Figure 4.18 Scenario 6 EV loads charging schedule

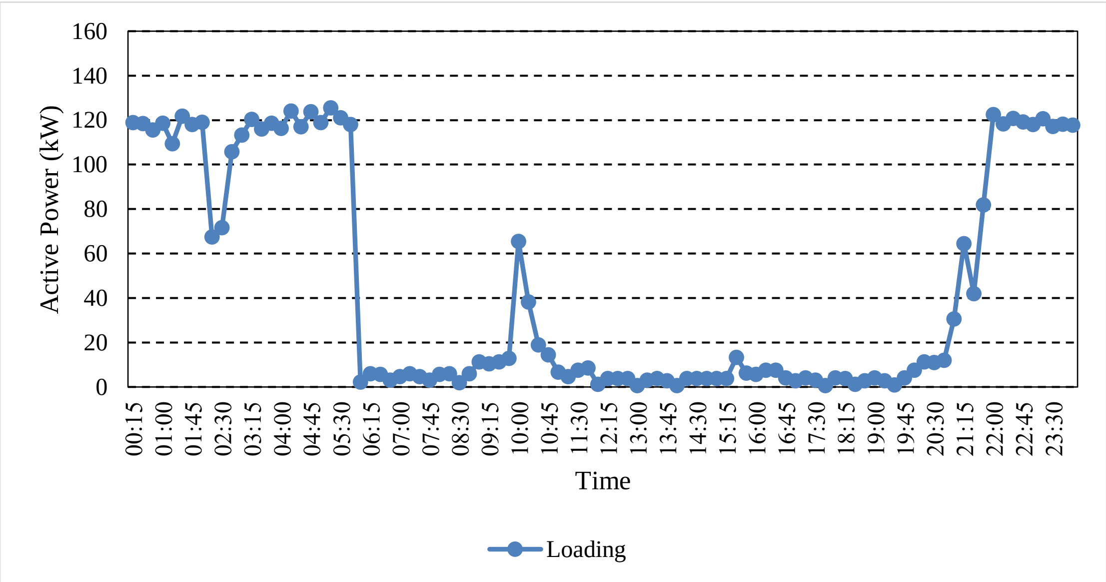

Figure 4.19 Scenario 6 DTR's loading curve

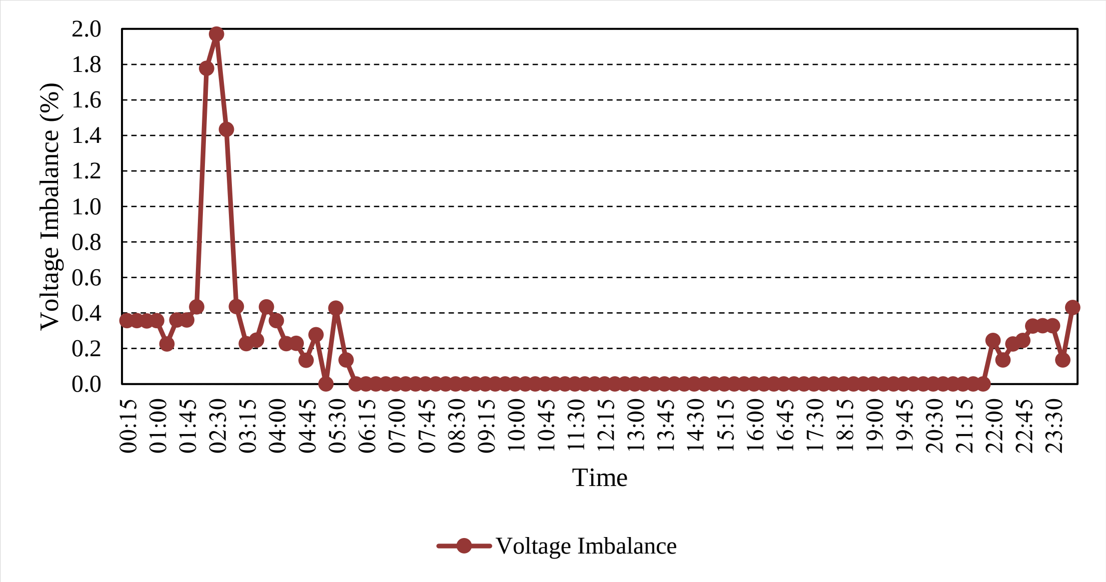

Figure 4.20 Scenario 6 DTR's voltage imbalance curve

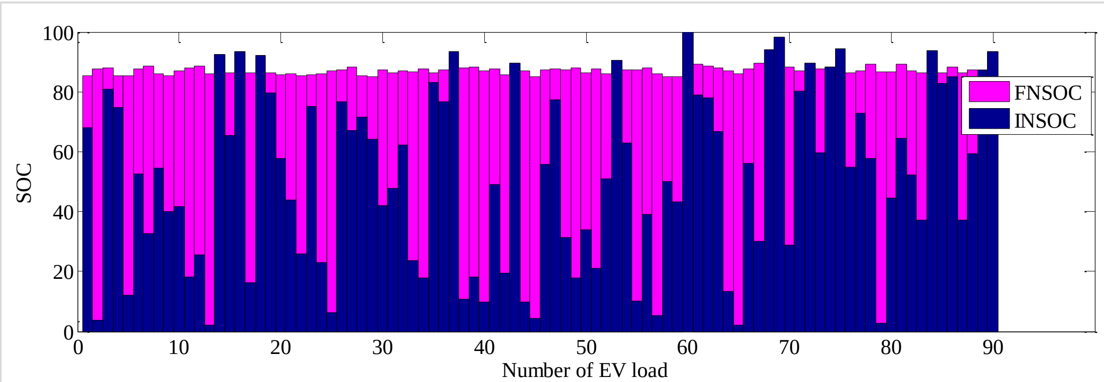

Figure 4.21 Scenario 6 EV's battery SOC chart

Table 4.6 Scenario 6 EV load result

Description	Value	Unit
Number of EV load	30	Set/Phase
TEMS	With	
Plug in time	Exponentially distribute from 10 - 12 p.m.	
Unplug time	6 a.m.	
Minimum value of FNSOC	76.20	%
Mean of INSOC	49.59	%
Mean of FNSOC	84.91	%
Customer KPI	76.69	%
Utility KPI	74.48	%

Scenario 7: With 35 EV load/phase and a control algorithm, random SOC, all EV load starts to charge at 10 p.m. and unplug at 6 a.m.

Figure 4.22 shows EV loads charging schedule with a TEMS that they exponentially distribute to charge from 10 - 12 p.m. and unplug at 6 a.m. Figure 4.23 shows a DTR's loading curve with 35 EV loads/phase, with a TEMS. It does not overload at all time. Figure 4.24 shows a DTR's voltage imbalance not more than the standard. Figure 4.25 shows EV's battery SOC chart that a DTR with TEMS cannot cover EV load and cannot all fully charge at 6 p.m. Means of final stage of charge is 78.87%. The statistics of Scenario 7 shown in Table 4.7.

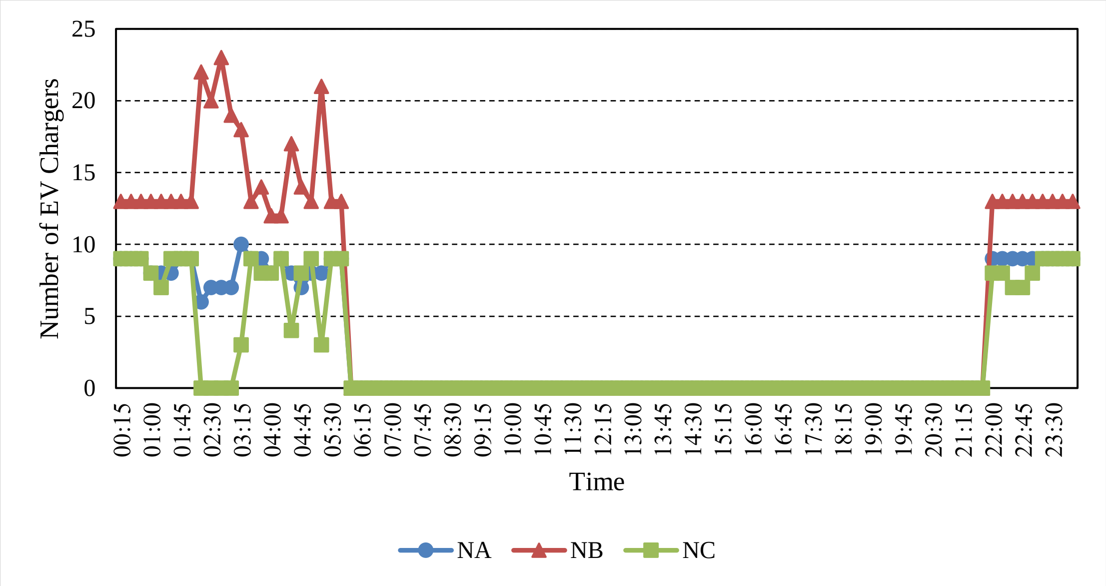

Figure 4.22 Scenario 7 EV loads charging schedule

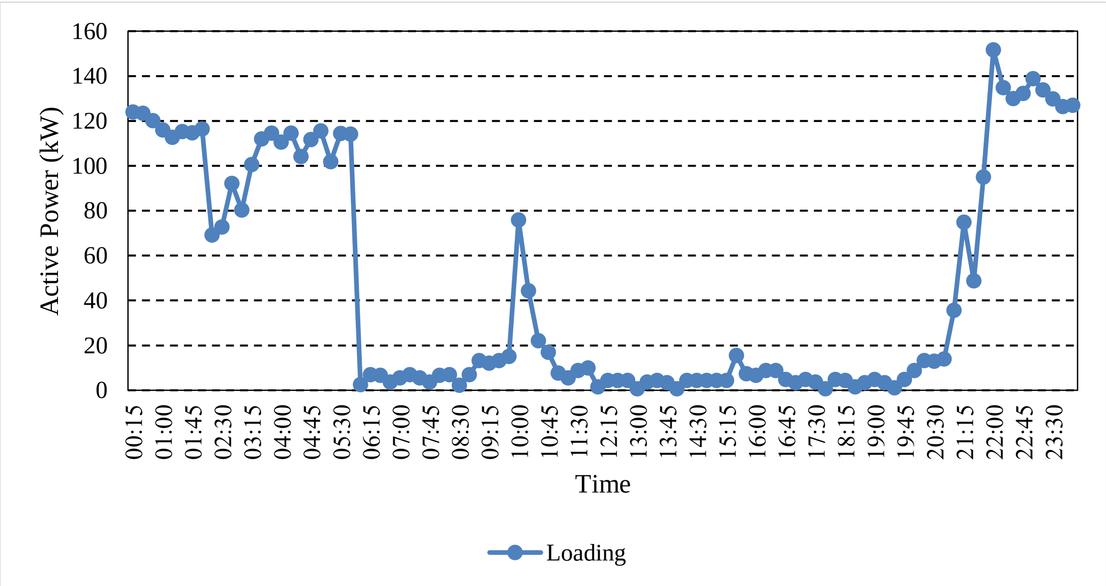

Figure 4.23 Scenario 7 DTR's loading curve

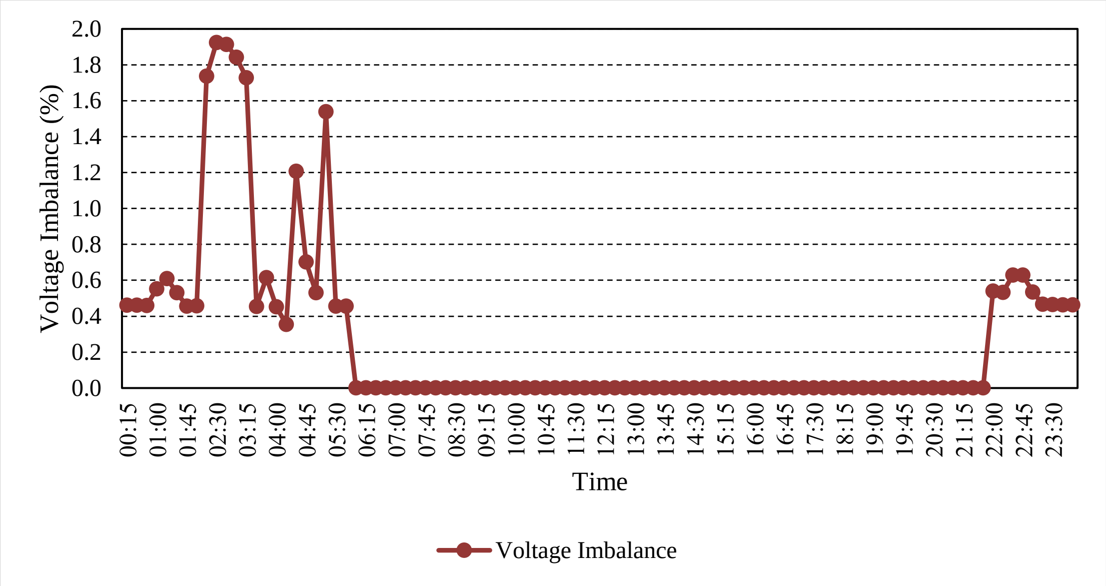

Figure 4.24 Scenario 7 DTR's voltage imbalance curve

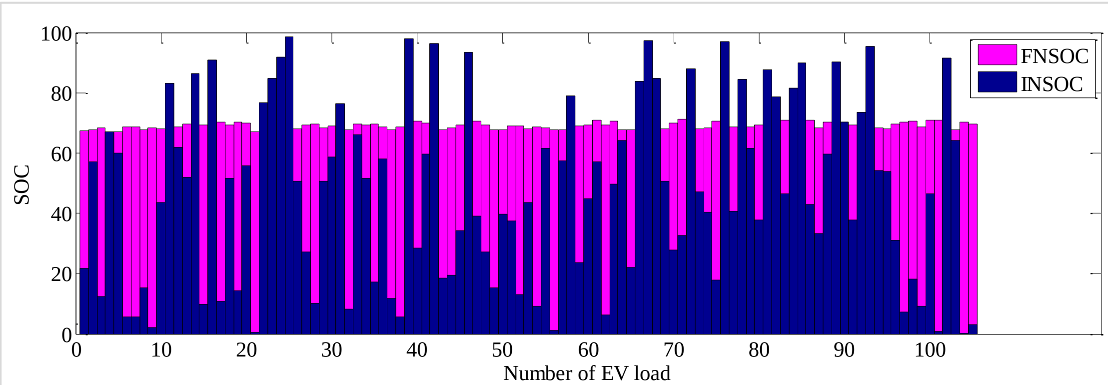

Figure 4.25 Scenario 7 EV's battery SOC chart

Table 4.7 Scenario 7 EV load result

Description	Value	Unit
Number of EV load	35	Set/Phase
TEMS	With	
Plug in time	Exponentially distribute from 10 - 12 p.m.	
Unplug time	6 a.m.	
Minimum value of FNSOC	62.64	%
Mean of INSOC	49.62	%
Mean of FNSOC	78.87	%
Customer KPI	33.23	%
Utility KPI	75.65	%

4.3 Result Discussion

The comparison result of the investigating scenarios as shown in Figure 4.26 – 4.31 and Table 4.8. The discussion of the result is as follows:

1. Figure 4.26 shows in case of without a TEMS, the utility have to limit the number of an EV load per phase according to Table 3.3.
2. Figure 4.27 and 4.28 show that when the number of an EV load with a TEMS are more than 20 set/phase, the customer KPI will decrease. The utility has to plan to install a new distribution transformer for them.
3. Figure 4.29 and Table 4.8 show the comparison of the Customer KPI, the Utility KPI, the mean of FNSOC, and the mean of INSOC. When increasing the number of EV load, the Utility KPI will increase contrast with Customer KPI.
4. Figure 4.30 shows the DTR’s loading curve of investigates scenarios that it do not overload at all time.
5. Figure 4.31 shows the DTR’s voltage imbalance curve of investigates scenarios that it do not more than the standard at all time.
6. If the customer can unplug an EV load later than 6 a.m., they will get higher FNSOC or fully charge.

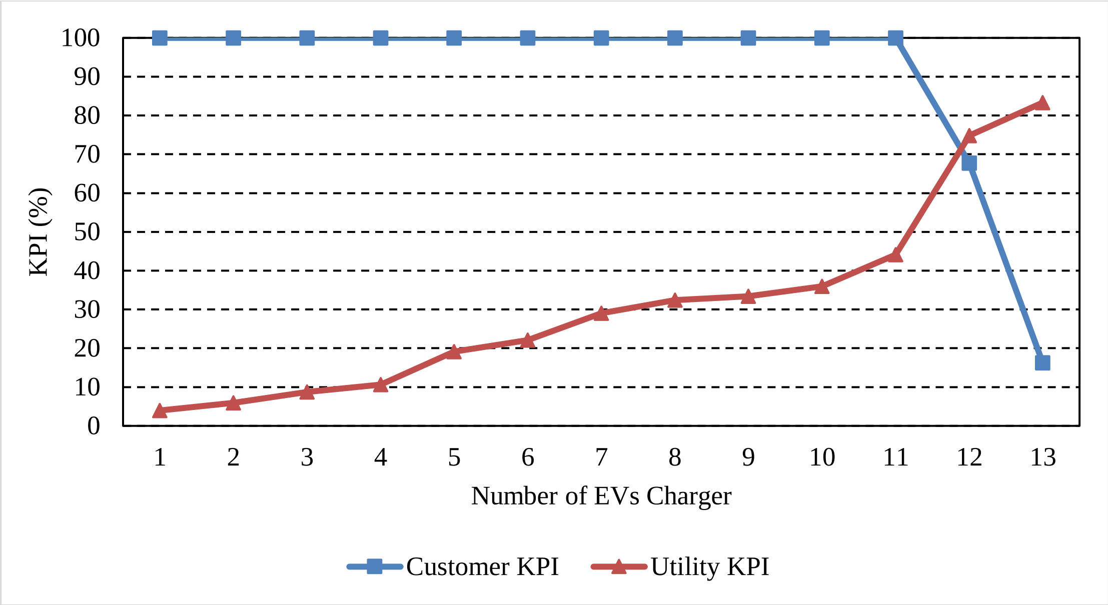

Figure 4.26 Satisfaction of customer and utility without TEMS

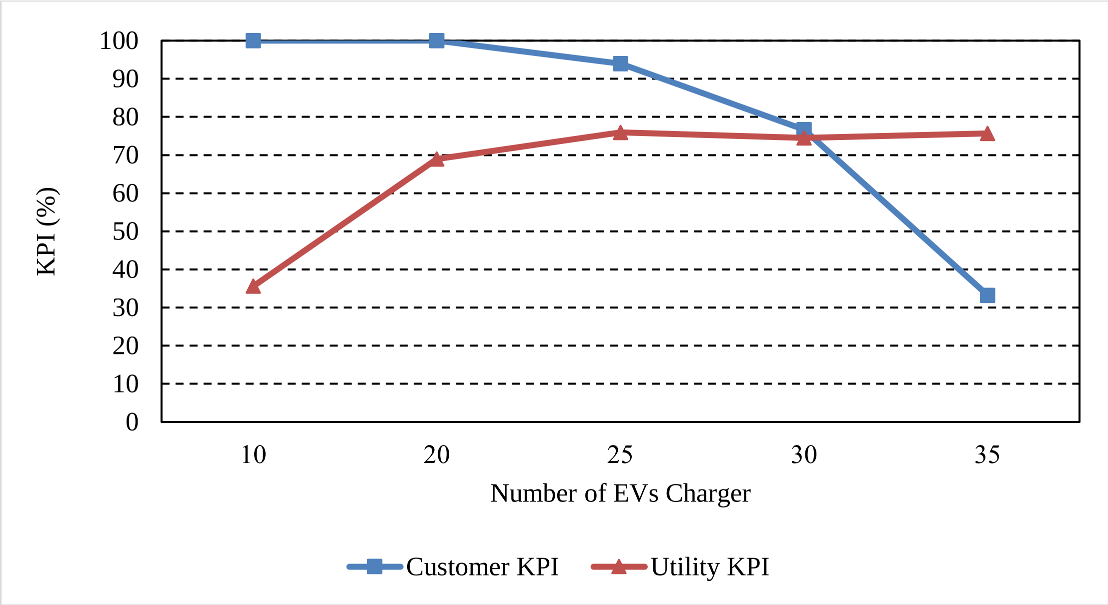

Figure 4.27 Satisfaction of customer and utility with TEMS

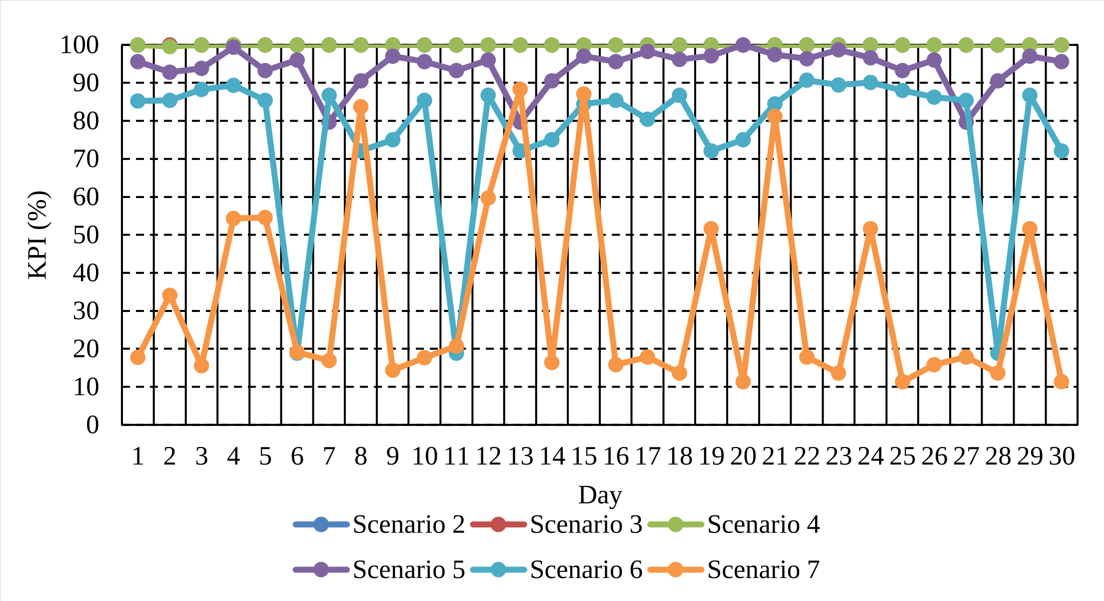

Figure 4.28 Satisfaction of customers

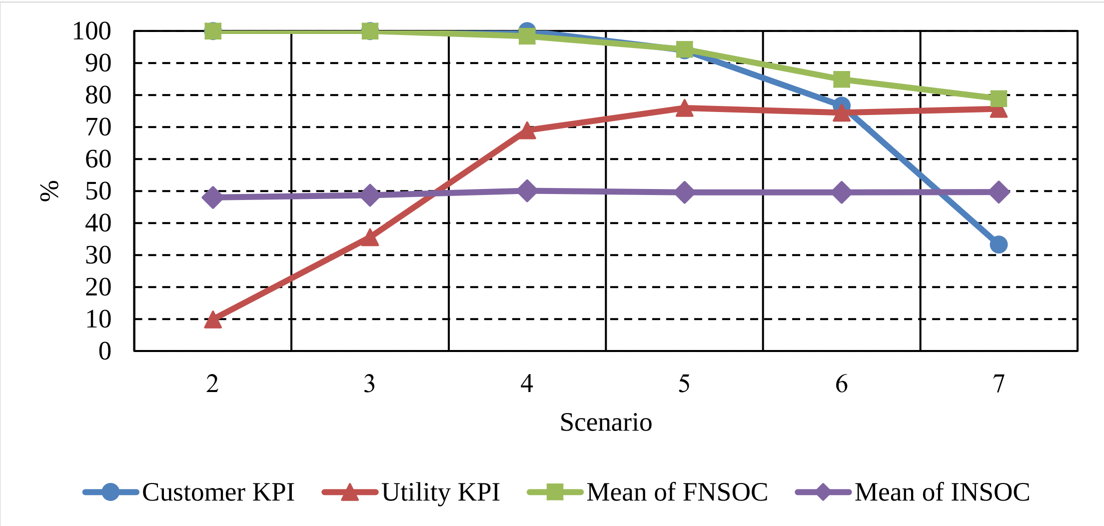

Figure 4.29 Means of study results

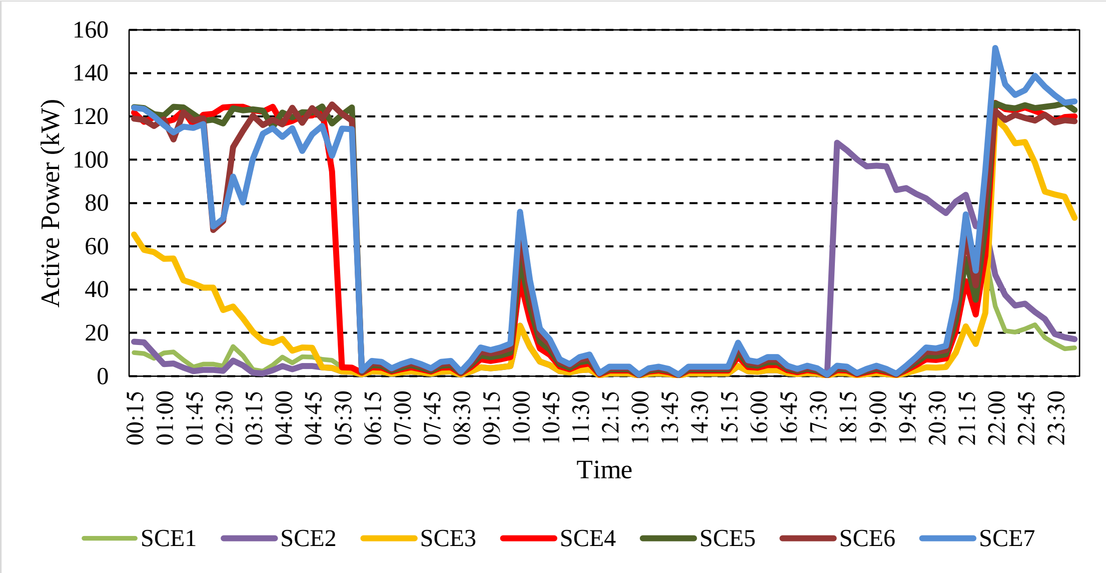

Figure 4.30 Comparison of DTR's loading curve

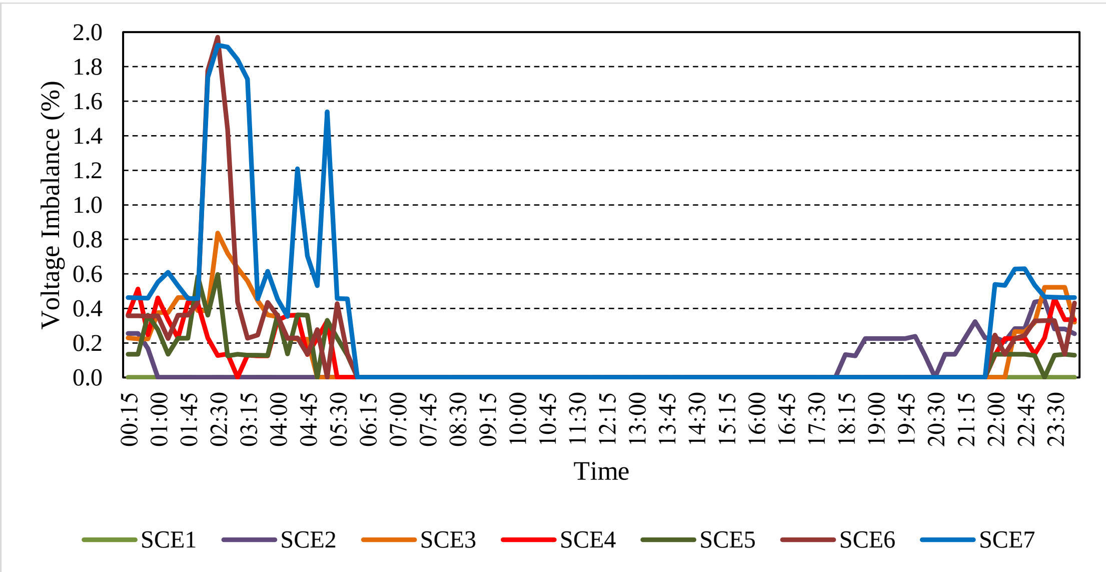

Figure 4.31 Comparison of DTR's voltage imbalance curve

Table 4.8 Comparison of a simulation result

Scenario	No. of EV load	TEMS	Plug in time	Mean of INSOC	Mean of FNSOC	Minimum value of FNSOC	Customer KPI	Utility KPI
1	-	N	-	-	-	-	-	-
2	10	N	6 p.m.	47.99	100	100	100	9.90
3	10	Y	10 - 12 p.m.	48.70	100	100	100	35.60
4	20	Y	10 - 12 p.m.	50.07	98.37	97.64	99.99	68.95
5	25	Y	10 - 12 p.m.	49.57	94.27	79.83	93.95	75.94
6	30	Y	10 - 12 p.m.	49.59	84.91	76.20	76.69	74.48
7	35	Y	10 - 12 p.m.	49.62	78.87	62.64	33.23	75.65

Chapter 5
Conclusions and Recommendations

In this chapter, we conclude the result of this thesis. Then, we propose the direction of the future work.

5.1 Conclusions

In this thesis, we divide our study into two parts. In the first part, we study the impacts of an EV load on a DTR without any coordination among the EV chargers and the DTR (i.e., without a TEMS). In the second part, we propose a charging schedule algorithm that has a better performance due to coordination between EV chargers and DTR (i.e. with a TEMS).

Without TEMS

An EV load in this study is a single phase EV home charger. It consumes a continuous power of 3.5 kW, for 6 hours until it is fully charged. Case 3 and 5 in Chapter 3 shows, if a customer plug in an EV load on only one phase or two phase, a utility and a customer may face with the voltage imbalance. Case 2 shows, if a utility does not control the number of an EV load, the DTR may overload at plugin time or peak period. Table 3.3 shows the maximum number of an EV load per phase that a utility can use it as a guideline to control a number of an EV load.

With TEMS

The charging strategy algorithm module has developed for generating the charging schedule of an EV load that can be used as a TEMS at a DTR. The loading and voltage imbalance module have developed to check the loading and voltage imbalance at a DTR from an EV load. Both of the modules have to work together when generates the charging schedule by a TEMS at a DTR.

When there is high penetration of an EV load, a utility has to install an Advanced Metering Infrastructure (AMI) that is working with the TEMS to control the number of an EV load to mitigate an impact and to meet the demand of a utility's DTR under control algorithm of coordinating charge. A customer will choose the TOU tariff instead of the normal tariff because they will pay the energy cost less than the normal tariff. The cheap price (off peak price) start from 10.00 p.m. - 9.00 a.m. that a TEMS start to operate in that period.

The result from scenario 5 shows, if a customer unplugs at 6.00 a.m., they may get almost fully SOC. If they can wait until 7.00 – 8.00 a.m., they will get fully SOC.

The result from scenario 6-7 shows, if an EV load has high penetration, the utility will have to install a new DTR for them.

The result from investigating scenarios show that if a utility does not install a TEMS at a DTR, it may overload and face with voltage imbalance at a DTR. If a utility installs a TEMS at a DTR, it can manage a base load and an EV load and it can control the loading and the voltage imbalance in the standard. A utility has to monitor a statistic of SOC, such as mean, standard deviation for planning to invest a new DTR.

In summary, when there is low penetration on an EV load, a utility has to control the number of EV load in each phase that does not more than the maximum number of an EV load per phase as Table 3.3. Furthermore, when there is high penetration of an EV load, a utility has to install the Advanced Metering Infrastructure (AMI) or the Smart Grid that is working with the DTR Energy Management System (TEMS) to mitigate an impact and to meet a limitation of a DTR.

5.2 Recommendations

Future work is as follows:

1. Implement a forecast algorithm of a base load to improve an accuracy of the TEMS and extend to use with DTR size 50, 100, 160, and 250 kVA.

2. Implement the system to read the SOC at an EV’s battery.

3. Study the relation between the statistic of SOC and the satisfaction of a customer.

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