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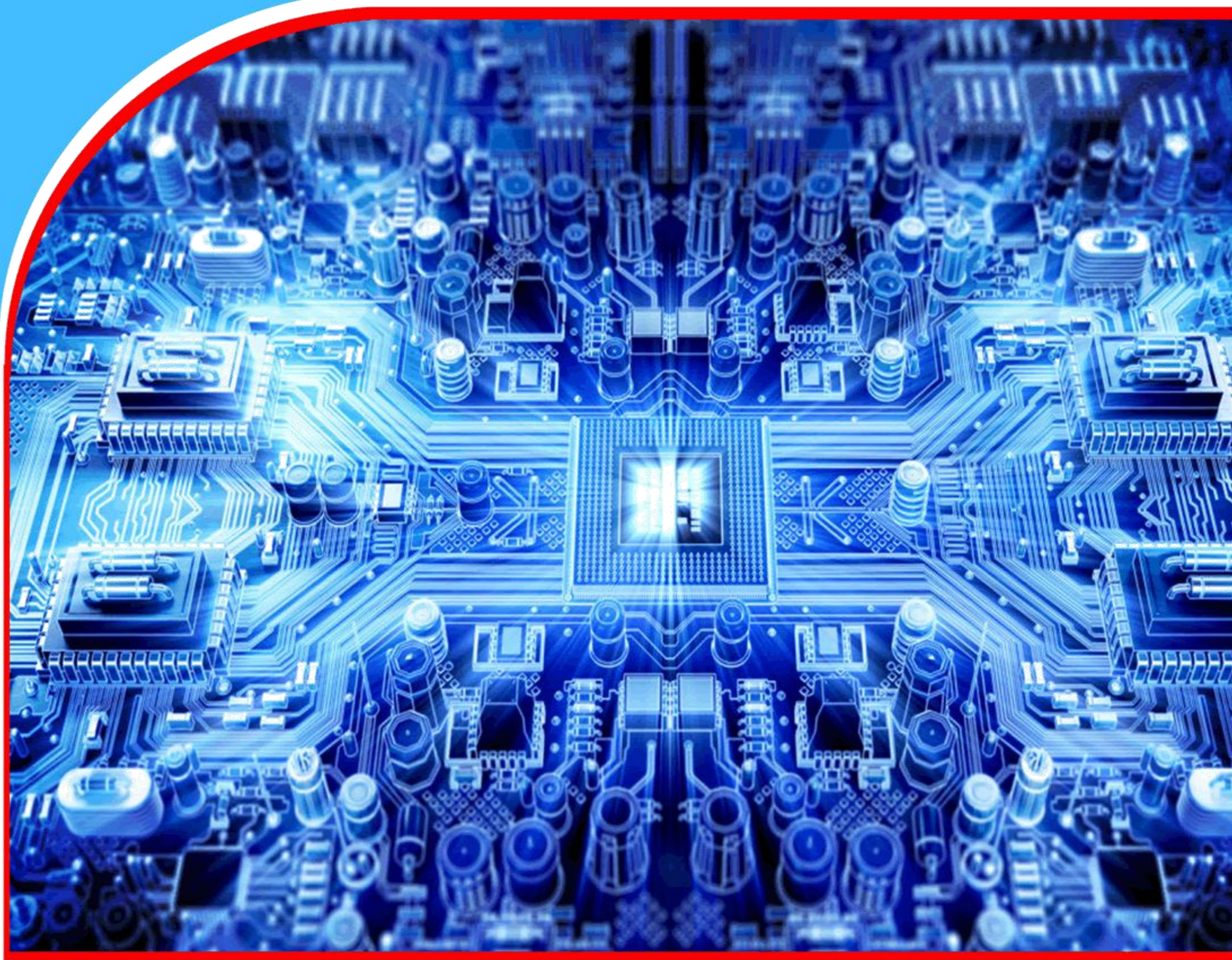

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ABSTRACT

Purpose: This paper investigates the impacts of electric vehicles integration in Rwandan Power system by assessing harmonic distortion, power loss, system loading, and voltage stability.

Methodology: Distribution network test was conducted on 34 buses taken from KINIGI feeder of Camp Belge substation in northern corridor of nation grid by using ETAP software.

Findings: The test came up with locating electric vehicles charging stations by taking into account the total harmonic distortion, transformer loading, voltage sensibility factor and the power loss where 4, 1, 2, 2, and 1 vehicles are located at buses 19, 20, 23, 25, and 26 respectively. The study determined the location of charging stations to enhance technical perspectives while implementing policies as policy maker motivates the public to shift from diesel powered EV to mitigate greenhouse gases emissions and fuel resources scarcity.

Recommendations: The number of integrated EVs has been shown to be low compared to the demand for EVs and the industry's annual target of 1000 EVs per year. This requires a utility to manage the proposed load increase by planning for the power generation, transmission and distribution infrastructure. In addition, EV charging stations generate current and voltage harmonics that affect negatively electrical equipment, nearby loads, and neighboring telecommunications lines. Harmonic filtering devices such as RHS, SC and hybrid devices built on RHS and SC are required in the distribution network to eliminate the effects generated by the harmonics.

Keywords: *Voltage stability, Electric vehicle, harmonic distortion, distribution network.*

1. INTRODUCTION

Transport in Rwanda is mainly based on transport and the energy sector in Rwanda classifies it among the top ten contributors of Green House Gases (GHG) emissions since it is currently based on diesel powered cars. In order to mitigate the greenhouse gases emissions, fossil-fuel resources scarcity and fuel dependency, various alternatives such as the use of electric vehicles (EVs) and fuel efficiency technologies were proposed by MoE in its Third National Communication Report to the United Nations Framework Convention on Climate Change. On the other hand, the EVs require electrical energy to be powered which in turns should be fossil fuel dependent and hence contribute to the GHG emissions. Therefore, the mitigation solutions should be applied to the electrical power generation by using renewable energy resources (Rwanda Environment Management Agency, 2011).

It is more than a century since existence of Electric vehicle (EV) technology climaxing commercially around 1900. However, due to the abundance of fossil fuels, IC technology advancements, and straightforward application of IC engines, EVs were put on hold and limited to golf carts and delivery vehicles (Rwanda Environment Management Agency, 2011). Figure 1 shows the progression timeline of the EVs worldwide.

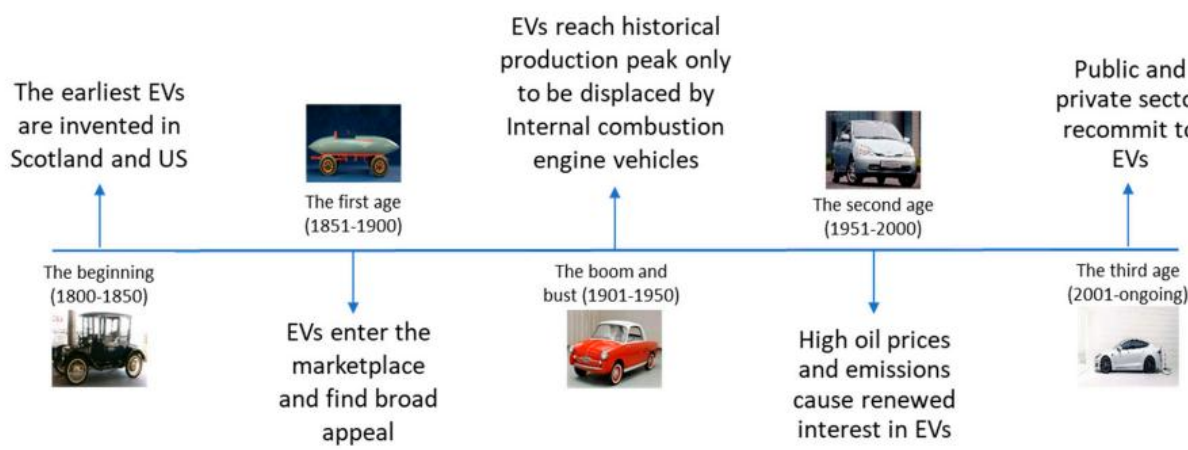

Figure 1: The evolution of electric vehicles (EVs) (Mohammad et al., 2020)

However, the uptake of electric vehicles (EVs) is still gradual as a result of variables like high capital costs, battery decline, and inadequate infrastructure for charging among others. Several policies and inducements are made available by governments around the world to encourage the uptake of EV and to keep these obstacles at bay from grasping a complete shift to electrified transportation. As articulated in Vision 2050, Rwanda committed to be a carbon free nation by the end of this vision and aims to reduce GHG emissions by 38% compared to business as usual by 2030 and Electric vehicles are thought to account for 9% of all possible energy-related emissions mitigated under the country's ten years climate action plan. It is against this background that the Rwanda Environment Management Authority (REMA) took carriage of its first electric vehicle to be used for the purpose of supporting the institution's mandate of environmental protection and has urged governmental and private institutions, as well as community, to consider switching to electric vehicles and participating in the fight against air pollution (Rwanda Environment Management Agency, 2011; Fabien, 2019).

2. METHODOLOGY

2.1 Distribution Voltage Stability

When there is voltage instability phenomenon, the network bus voltage lessens progressively and uncontrollably. Usually, unstable state is due to the sudden disturbances, fault conditions, single or multiple contingencies, line overloading or load increases. The voltage of all system buses must be within acceptable bounds, according to a voltage stability criterion commonly employed in stability studies. Voltage stability is a local phenomenon, although it can lead to significant voltage breakdown in specific instances (Schlabbach et al., 2011).

2.1.1 Voltage Sensitivity Factor (VSF)

It is one of the voltage stability indicators obtained from the PV curve which shows the trend of voltage alteration with rising active power as shown in figure 2. To plot the PV curve, the voltage of all buses in the system should be determined by using one of the load flow analysis method.

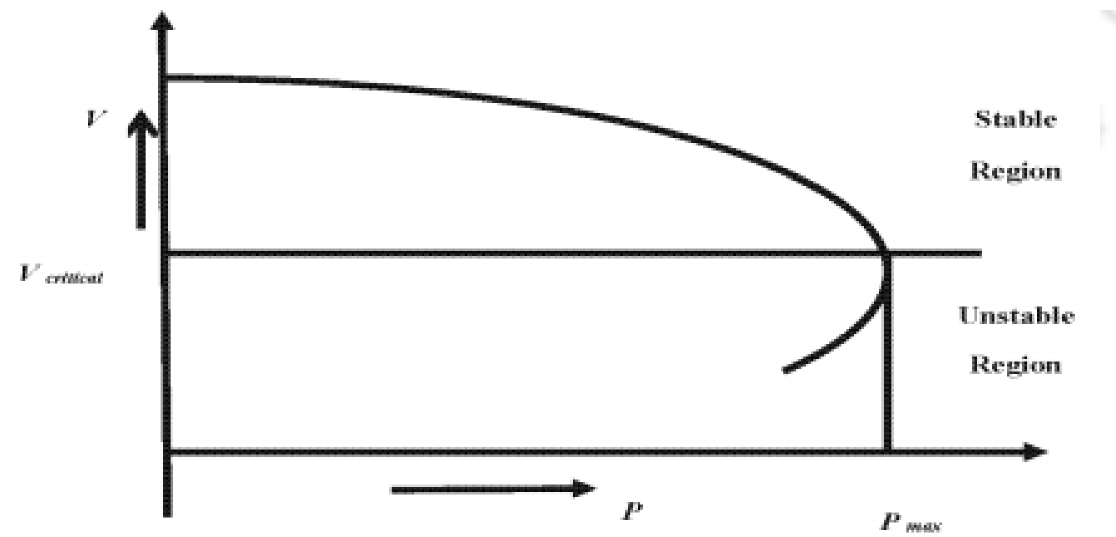

Figure 2: Bus PV curve (Deb et al., 2018)

On the PV curve, the voltage decreases as the active power increases up to the critical point $(P_{max}, V_{critical})$ corresponding to the limit of stable operation. The ratio of change in voltage and change in loading is called VSF expressed mathematically as (Deb et al., 2018),

$$VSF = \left|\frac{dV}{dP}\right| \forall P < P_{\max} \qquad (1)$$

A high value of VSF indicates that there is a considerable voltage drop thereby signifying weakness of the bus even for a small change in loading. For a distribution network to be stable in terms of voltage stability, the voltage of all buses must be within an acceptable limit. The loading corresponding to this voltage range is called the realistic loading margin of the system (Van Cutsem & Vournas, 2008).

2.2 Harmonic Distortion

Electric vehicle charger is one of nonlinear types of load on distribution network. This type of load affects the power quality of the power system due to the current it draws from the system which is not a perfect sine wave. Since the current waveform deviates from a sinusoidal waveform, the voltage waveform is distorted.

2.2.1 Total Harmonic Distortion (THD)

Electric Vehicles utilize power electronics within the charge controllers that link the vehicle's electric system with the grid. For Level I and Level II chargers, an on-board AC-DC controlled rectifier couples with the electric service via a single-phase connector to charge the vehicle. For Level III charges (DC Fast Chargers), electronics in the charge controller control the charging process. In all cases, the charge controllers' harmonic distortion introduced into the distribution network is assessed in terms of THD. Normally the charger THD changes in accordance with the charging cycle as the firing angles of the power electronics switches alter in reaction to the various phases of the charging cycle. Further, the THD on a utility feeder builds up when many EVs are plugged into the same service. The following equation shows how to compute the THD for individual charger (Schlabbach et al., 2011; Bass & Zimmerman, 2013).

$$I_{THD} = \frac{\sqrt{\sum_{n=2} I_n^2}}{I_1} * 100\% \tag{2}$$

The harmonic distortion impacts distribution devices, especially capacitors, metering, transformers, power cables, relaying and switchgear as well as nearby loads, particularly power electronics devices and motors drives. The standardized value of the maximum level of THD to be adopted for planning, development and connections on the distribution network are given in the table below (Electricity Association, 2005).

Table 1: THD planning limits

System voltage	THD limit
400V	5%
6.6kV, 11kV and 20kV	4%
22kV to 400kV	3%

2.3 Power Loss

The losses in electrical distribution consist of technical and non-technical losses. Technical losses are made of fixed technical losses and variable technical losses and refer to the conductors' energy dissipation, used power lines equipment and magnetic losses in the transformers. They are directly dependent on the grid characteristics and the mode of operation (Moreira Rodrigues et al., 2021); Van Tsai et al., 2010). The contribution of variable losses ranges from 66 to 75% of total losses on distribution network and consist mainly with Cu losses which vary with the quantity of electricity distributed. The mathematical expression for calculating the line losses at bus j is given in the following equation (Deb et al., 2018).

$$P_j = I^2 r \qquad (3)$$

And the total power losses of a distribute on system of n busses are given by

$$P_t = \sum_{j=1}^{n} P_j \qquad (4)$$

From the above equation, we can conclude that even a single bus's rise in load demand will result in a net increase in distribution network power losses.

2.4 Case Study

The model is taken at Camp belge substation in northern corridor of Rwandan network and the study is carried out at Kinigi feeder which is a 33KV line with 34 voltage buses.

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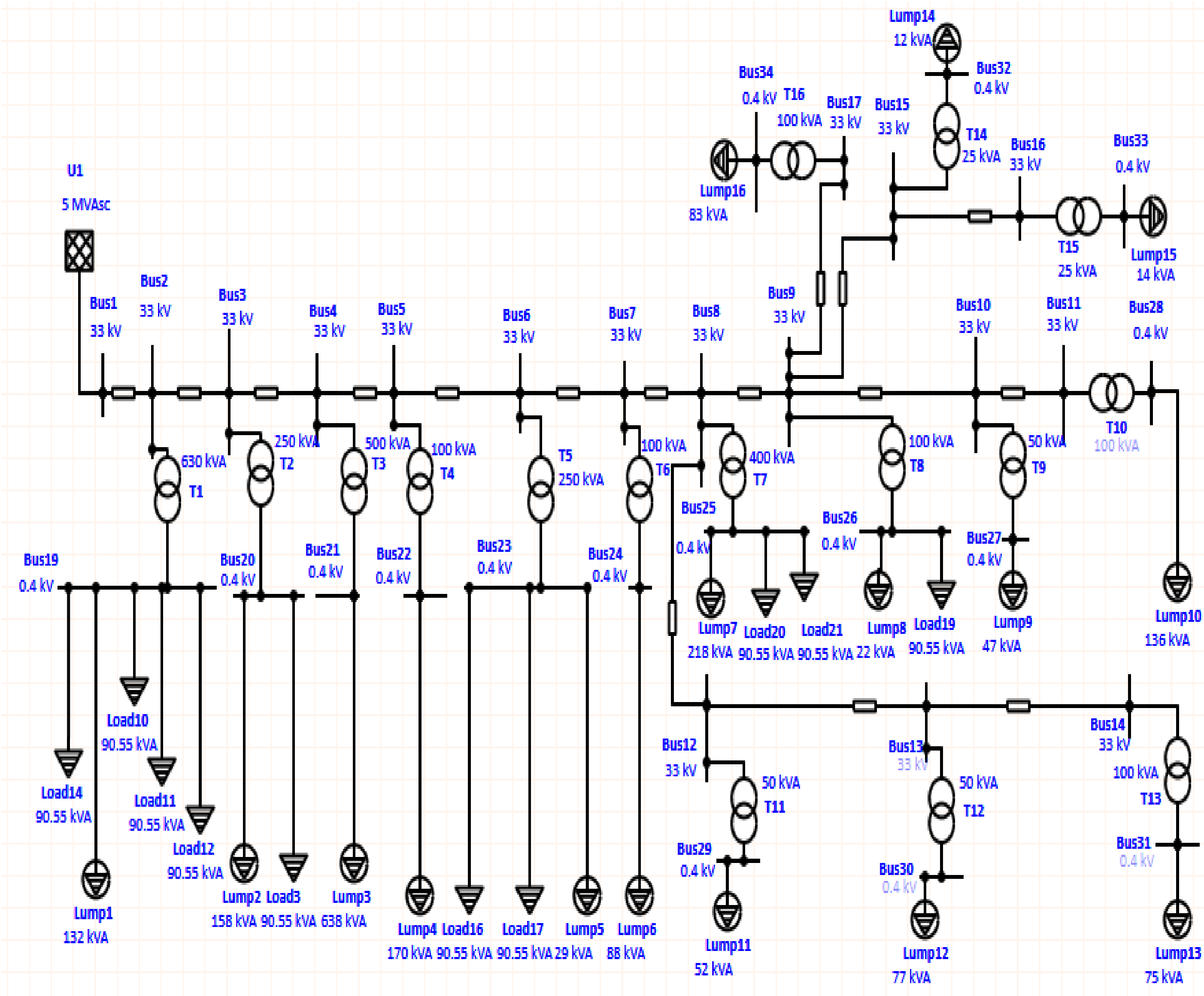

Figure 3: Distribution line model

3. RESULTS AND DISCUSSION

3.1 Transformer Loading

Table 2 shows the Transformer loading that is simulated by using ETAP software to show the status of output power at different buses as percentage of the input power supplied to the specific bus. The results show that transformers T3, T4, T10, T11 and T12 are already overloaded referring to their loading capability. Taking into consideration this fact, it is not a good idea to connect an EV at their buses. Hence addition load from EV can be integrated in the network through assessment of the remaining transformers.

Table 2: Transformer Loading

			Loading (input)		Loading (output)	
ID	Type	Capability (kVA)	kVA	%	kVA	%
T1	Transformer	630	132.5	21	131.7	20.9
T2	Transformer	250	158.7	63.5	157.5	63
*T3	Transformer	500	650.2	130	629.9	126
*T4	Transformer	100	170.7	170.7	169.4	169.4
T5	Transformer	250	29	11.6	29	11.6
T6	Transformer	100	88.1	88.1	87.8	87.8
T7	Transformer	400	219.1	54.8	216.9	54.2
*T10	Transformer	100	136.4	136.4	135.5	135.5
*T11	Transformer	50	52	104	51.9	103.8
*T12	Transformer	50	77.1	154.1	76.8	153.6
T13	Transformer	100	75.1	75.1	74.8	74.8
T14	Transformer	25	12	48	12	47.9
T15	Transformer	25	14	56	14	55.9
T16	Transformer	100	83.1	83.1	82.8	82.8
*Indicates a branch with operating load exceeding the branch capability						

3.2 Voltage Stability

V-Q sensitivity increases with increase in loading on the system, hence the integration of EVs has a limited value in other to keep the system stable since if the sensibility exceeds the limits at least from one buses the whole system becomes unstable with a possibility of system collapse once this condition persist.

Table 3: V-Q Sensitivity Analysis Report

		Without Evs		With Evs	
Bus ID	Rank	Voltage (%)	V-Q Sensitivity	Voltage (%)	V-Q Sensitivity
Bus31	1	0.99	1	0.99	1
Bus30	2	0.99	0.983	0.99	0.983
Bus28	3	0.99	0.976	0.99	0.976
Bus21	4	0.97	0.975	0.97	0.974
Bus33	5	1	0.973	1	0.973
Bus29	6	0.99	0.972	0.99	0.972
Bus25	7	0.99	0.97	0.99	0.97
Bus34	8	0.99	0.97	1	0.97
Bus32	9	1	0.97	0.98	0.969
Bus27	10	0.99	0.968	0.99	0.968
Bus26	11	1	0.963	0.99	0.963
Bus24	12	0.99	0.959	0.99	0.958

Bus22	13	0.99	0.953	0.99	0.953
Bus23	14	1	0.951	0.99	0.949
Bus20	15	0.99	0.944	0.99	0.943
Bus19	16	0.99	0.933	0.99	0.931
Bus9	25	1	0.025	1	0.025
Bus8	26	1	0.023	1	0.023
Bus7	27	1	0.017	1	0.017
Bus6	28	1	0.013	1	0.013
Bus5	29	1	0.01	1	0.009
Bus4	30	1	0.006	1	0.006
Bus3	31	1	0.002	1	0.002
Bus2	32	1	0	1	0

3.3 Harmonic Distortion

As shown in the table 4 and figure 4, the harmonic distortion before EVs integration were in normal operating range but when they are integrated, the harmonics increases to the level that they exceed the maximum allowable limits. Additional costs incur to address the harmonic distortion filters.

Table 4: System Total Harmonic Distortion Report

		Without Evs			With EV		
ID	kV	Fund. %	RMS %	THD	Fund. %	RMS %	THD
Bus 1	33.00	100.00	100.00	0.00	100.00	100.16	5.73
Bus 2	33.00	99.99	99.99	0.00	99.99	100.15	5.73
Bus 3	33.00	99.96	99.96	0.00	99.94	100.11	5.74
Bus 4	33.00	99.89	99.89	0.02	99.86	100.03	5.75
Bus 5	33.00	99.84	99.84	0.00	99.80	99.96	5.77
Bus 6	33.00	99.81	99.81	0.01	99.75	99.92	5.78
Bus 7	33.00	99.78	99.78	0.01	99.71	99.88	5.79
Bus 8	33.00	99.73	99.73	0.01	99.64	99.81	5.81
Bus 9	33.00	99.72	99.72	0.00	99.63	99.80	5.81
Bus 10	33.00	99.71	99.71	0.01	99.62	99.79	5.81
Bus 11	33.00	99.70	99.70	0.01	99.62	99.79	5.81
Bus 12	33.00	99.70	99.70	0.00	99.62	99.79	5.82
Bus 13	33.00	99.67	99.67	0.01	99.59	99.76	5.83
Bus 14	33.00	99.64	99.64	0.02	99.56	99.73	5.83
Bus 15	33.00	99.71	99.71	0.01	99.63	99.79	5.82
Bus 16	33.00	99.71	99.71	0.01	99.62	99.79	5.82
Bus 17	33.00	99.71	99.71	0.02	99.63	99.79	5.81
Bus 19	0.40	99.38	99.38	0.01	99.81	98.98	5.95
Bus 20	0.40	99.21	99.21	0.01	99.06	99.21	5.52
Bus 21	0.40	96.77	96.77	0.01	96.74	96.87	5.19
Bus 22	0.40	99.04	99.04	0.00	99.00	99.15	5.64
Bus 23	0.40	99.67	99.67	0.02	99.35	99.60	7.15
Bus 24	0.40	99.36	99.36	0.00	99.30	99.46	5.73
Bus 25	0.40	98.69	98.69	0.02	98.32	98.58	7.17
Bus 26	0.40	99.61	99.61	0.00	99.40	99.58	6.09
Bus 27	0.40	99.49	99.49	0.00	99.40	99.57	5.78
Bus 28	0.40	99.06	99.06	0.01	98.98	99.14	5.71
Bus 29	0.40	99.46	99.46	0.00	99.38	99.54	5.78
Bus 30	0.40	99.31	99.31	0.00	99.23	99.39	5.77
Bus 31	0.40	99.29	99.29	0.01	99.21	99.37	5.78
Bus 32	0.40	99.65	99.65	0.02	99.57	99.74	5.81
Bus 33	0.40	99.64	99.64	0.01	99.56	99.73	5.81
Bus 34	0.40	99.32	99.32	0.00	99.24	99.40	5.75

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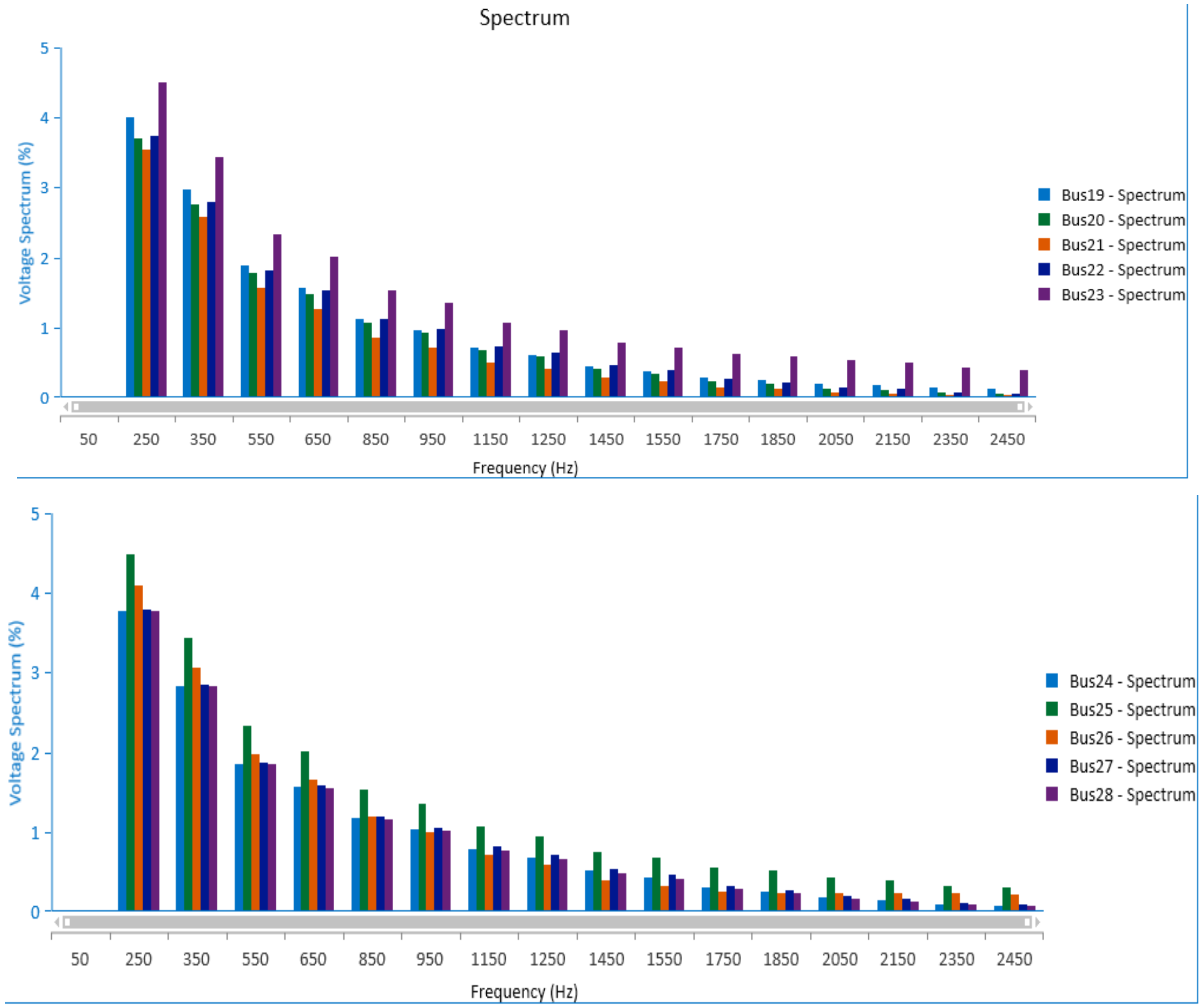

Figure 4: All buses harmonic distortion spectrum

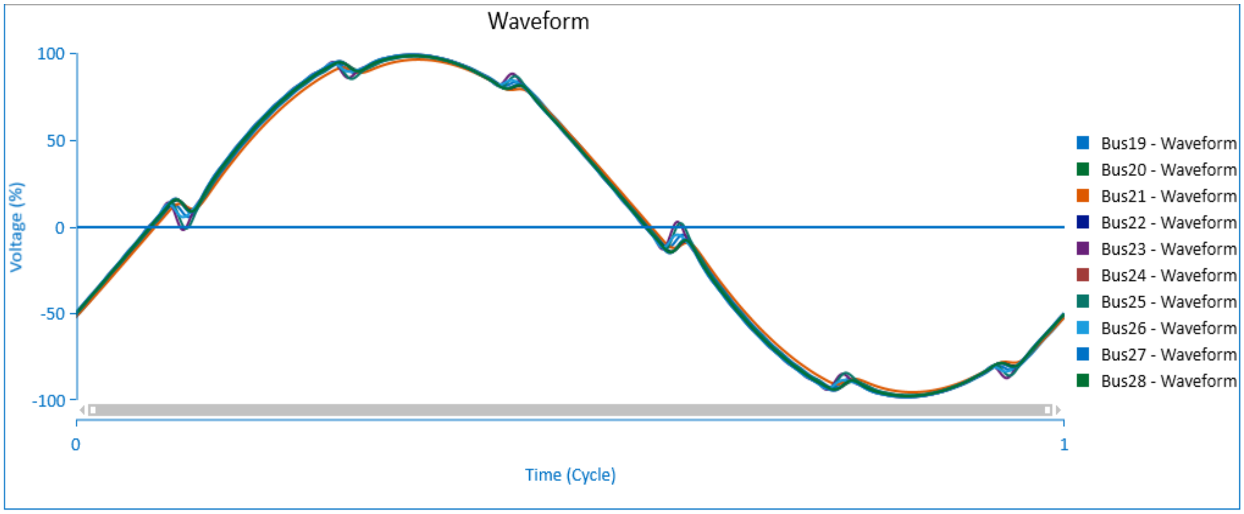

Figure 5: All busses Harmonic Distorted Waveform

3.4 Power Loss

The power loss consists of two components active and reactive power losses. The active power loss shifts from 5.7kW to 9.7kW and reactive power from -2.5kVAR to 31.2kVAR. This shows a rise of 4kW and 33.7kVAR active and reactive power loss respectively when EVs are integrated into the network.

Table 5: Branch Losses Summary Report

	Without EV		With EV	
Branch ID	**kW**	**kVAR**	**kW**	**kVAR**
Line 1	0.1	-0.1	0.2	0.0
Line 10	0.3	-4.1	0.5	-3.9
Line 11	0.0	-1.9	0.0	-1.9
Line 12	0.0	-2.2	0.0	-2.2
Line 13	0.0	-3.1	0.0	-3.1
Line 16	0.0	-6.6	0.0	-6.6
Line 17	0.0	-5.1	0.0	-5.1
Line 20	0.0	-9.9	0.0	-9.9
Line 22	0.0	-4.5	0.0	-4.5
Line 23	0.0	-1.7	0.0	-1.7
Line 25	0.0	-1.4	0.0	-1.4
Line 3	0.5	-0.8	0.8	-0.5
Line 4	0.8	-1.7	1.3	-1.2
Line 5	0.3	-2.5	0.7	-2.2
Line 7	0.2	-2.3	0.5	-2.0
Line 8	0.2	-2.3	0.3	-2.2
T 1	0.1	1.4	1.2	18.3
T 10	0.1	1.5	0.1	1.5
T 11	0.0	0.2	0.0	0.2
T 12	0.0	0.5	0.0	0.5
T 13	0.0	0.5	0.0	0.5
T 14	0.0	0.0	0.0	0.0
T 15	0.0	0.0	0.0	0.0
T 16	0.0	0.6	0.0	0.6
T 2	0.1	2.0	0.3	4.7
T 3	2.3	33.8	2.3	33.8
T 4	0.2	2.3	0.2	2.3
T 5	0.0	0.1	0.2	3.4
T 6	0.0	0.6	0.0	0.6
T 7	0.3	3.9	0.8	12.1
T 8	0.0	0.0	0.1	1.0
T 9	0.0	0.2	0.0	0.2
Total	**5.7**	**-2.9**	**9.7**	**31.2**

3.5 Location of Charging Stations

The charging stations are located by gradually loading each and every bus and determine whether the power quality is within acceptable limits.

Taking into account the voltage stability, power loss, transformer loading and harmonic distortion, EVs are located on the load point (buses) as shown by table 6 for the sake of keeping the power quality within safe limits.

Table 6: EV charging stations location

Bus 19	Bus 20	Bus 23	Bus 25	Bus 26
4	1	2	2	1

3.6 Determination of Appropriate Charging Hours for Electric Vehicles

The data collected from the site shows that the tariff for industrial customers depends on two factors to take into account the energy consumption as well as the maximum demand offered to the grid by the industry. The maximum demand is charged differently on the basis of connection period in three categories viz off peak, shoulder and peak period. The least chargeable period is during off peak period and the cost rises gradually from it to the peak period. Since EVs substation operates as industrial customers, the substation owners have to schedule the charging period so that most of EVs are connected from 11:00 PM to 07:59 AM to lessen the cost using EVs affordable.

4. CONCLUSION

The effect of EVs integration in distribution network is investigated though voltage sensitivity, power loss, system loadability and harmonic distortion studies. Simulation of the results were conducted on a 34 buses distribution system via ETAP software. The results show an increase of harmonic distortion and bus loadability due to increased load on the system and charging cycles of EV batteries. The voltage stability is less affected by EV integration since reactive power changes is not significantly high to the level of causing significant voltage sensitivity deviation and the power loss increases as number of EVs on the network increases. These results helped the author to locate EVs on specific buses in order to minimize their impact on power quality of the system but keep enjoy their positive traits to the environment. Finally, appropriate charging period has been identified from power profile and utility tariff analysis in order to minimize the cost of electricity incurred since penalties are charged for industrial loads connected during off peak period.

5. RECOMMENDATIONS

It was indicated that less number of EVs is to be integrated compared to electric vehicle demand and industry yearly target which sits at 1000 EV assembled per year. This requires power utility to respond to the load growth by planning for generation, transmission and distribution infrastructure. Furthermore, EVs charging stations produces current and voltage harmonics which affects electrical equipment, nearby loads and neighboring telecommunication lines. Harmonic filtering devices such as RHSs, SCs and hybrid devices built on RHSs and SCs are required in distribution network to cope with the effects produced by harmonics.

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