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Power Quality Model of Distributed Networks Integrated with Renewable Energy Sources

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Abstract- The integration of renewable energy sources (RES) into the power system distribution network has proven beneficial to all the power sector players. These include reduced greenhouse gas emission, reduced transmission and distribution losses, delivery of clean power to consumers due to proximity of loads to the generators, and deferred investments by distributed network operators. The continued integration of RES has been enhanced by the inability of conventional energy to meet increasing power requirements, the need for clean energy, low power generation costs due to technological advancements, and favorable government policies encouraging investment in the renewable energy sector. This integration, however, necessitates the reconfiguration of the distribution network since RES cause reversed power flows, instability among other power quality concerns. This transformation will rely on studies conducted on the behavior of grids integrated with renewable energy sources. This paper examined the impact on harmonics and flicker of low voltage (LV) and medium voltage (MV) networks caused by the integration of solar, wind and gas micro-turbine generators. This was realized by integrating the RES at selected locations of the IEEE-33 bus system and carrying out harmonics and flicker analysis using DigSILENT Power Factory software. Obtained results indicated increased harmonic distortion and flicker levels on LV and MV networks dependent on the type, location, penetration level and whether a single-type of RES or combination of RES was installed…

Keywords- integration of renewable energy sources, IEEE 33-bus distribution network, power quality analysis.

I. INTRODUCTION

The contribution of RES to Kenya's energy mix is continuously increasing. The continued harnessing of energy from RES is due to conventional energy sources' inability to meet the growing power requirements crucial to economic growth. The primary energy sources in Kenya are petroleum, biomass and electricity [1].

The installed capacity from renewable energy generation technologies as of 2018 was around 2000MW, which constitutes 85% of the total electricity generated [2]. Access to electricity from the grid and off-grid solutions stands at 75% [2, 3]. Biomass resources (firewood and charcoal) are the Primary energy source in rural areas and contribute over 70% to national energy demand [4]. The estimated renewable energy resources potential is, however, hugely unexploited. This grants opportunities for investment in the energy sector. Additionally, Kenya has reviewed her energy policy to: promote energy extraction from renewable energy resources, regulate the players involved, and ensure effective use and conservation of energy [5].

RES sources integrate into power systems networks at the distribution network level. RES's key benefits include delivering clean and dependable power to consumers, deferment of investments on transmission and distribution networks, and reduced transmission and distribution losses due to energy generation close to load centres. The integration of RES into MV and LV networks requires changes in the planning and operation of grids [6, 7].

The reconfiguration of distribution grids addresses reversed power flows, flicker, and instability, among other power quality problems that may arise due to RES connection. Power quality problems are prevalent in weak grids characterized by a low short-circuit ratio. RES use power electronic devices to interface to the distribution grid, introducing harmonics and flicker in the system. The level of harmonic distortion introduced depends on the type of RES, location, and the number of RES generators installed [8-10].

The determinants for flicker emission levels include the type of RES installed, inverter control characteristics and distribution grid's short circuit capacity [11, 12].

This paper examined the impact on harmonics and flicker of MV and LV networks caused by integrating solar, wind and biomass micro turbines generator systems. Buses 6, 15 and 25 were selected for the placement of RES to reduce active losses [13, 14].

Two case studies were developed whereby the first case study aimed at increasing the penetration level of each RES type and the second considered integration of the three RES types in various combinations at the same time.

II. RES TECHNOLOGIES IN KENYA

Kenya is leading the African continent in harnessing energy from RES. Wind, Solar, Hydro, Biomass and Geothermal are some of the RES abundantly found in Kenya. From the various RES technologies types, solar, hydro, wind and biomass RES types attract the most significant attention in distributed generation networks since they are technically feasible.

The amount of energy harnessed from RES varies from a few kilowatts to several megawatts.

1. Solar

Kenya experiences high insolation levels due to its location along the equator [15]. According to Oloo [16], 70% of Kenya's land area insolation potential is approximately 5.5 KWh/m2/day with an annual average of 6.98 kWh/m2. The exploitation of solar energy remains limited. As of 2019, the installed capacity of solar was approximately 50.25 MW.

However, the Energy and Petroleum Regulatory Authority projects a 15% growth rate of installed solar PV due to decreasing solar PVs prices, Energy (Solar Water Heating) Regulations 2012 and commercialization of solar energy. Solar energy is considered a good option for rural electrification and decentralized applications.

2. Wind:

Kenya has one of the most immense wind energy generation potentials in Africa. Depending on the turbine capacity factor, potential output is 22,476 TWh/year (>20%), 4,446 TWh/year (>30%) and, 1,739 TWh/year (>40%) in the windiest areas [17]. Additionally, Kenya has excellent wind regimes, with the Rift Valley being the windiest with average wind speeds of above 9 m/s at 50m high. Nearly 25% of the country is well suited to the current wind technology.

Currently, Kenya is experiencing a swell in wind energy installations that generate electricity to feed into the grid. The Lake Turkana Wind Power Project (310 MW) and Ngong Hills Wind Power Project (25.5 MW) are the current wind farms connected to the grid, with Kipeto Project on course. Additionally, some 80-100 small wind turbines (0.4 – 6 kW) have been installed often as components of a Photovoltaic (PV)-Wind hybrid system with battery storage [17].

3. Biomass:

Biomass fuels are the dominant primary energy source in Kenya, with wood-fuel and agricultural residues contributing over 70% of the total primary energy consumption. Biomass consists of wood-fuel (firewood and charcoal), biogas, biofuels, municipal waste, agricultural and industrial residues.

Power generation potential from forestry and agro-industrial residues is substantial. The total energy produced through cogeneration using sugarcane bagasse in various sugarcane companies as of 2019 was 193 MW [2]. Biogas potential has been identified in municipal waste, coffee and sisal production and the total installed capacity ranges between 29-139 MW, accounting for about 3.2-16.4% of total electricity production [2].

III. MODELLING OF RES

1. Modelling of the Solar PV system:

Researchers have developed several models of modelling the solar cell; however, the single diode model (SDM) is the most preferred due to its simplicity [18, 19]. Authors in [19, 20] describe the SDM solar cell equivalent and its model equations. In practice, solar PV arrays comprise solar cells connected in parallel or series to boost output voltage or current, respectively.

In DigSILENT PowerFactory software, the static generator models the solar PV since it has non-rotating parts. The developed solar PV system was configured to generate 0.5MW at 50Hz and was connected to the IEEE-33bus system at 0.4kV. To perform harmonic and flicker simulations in PowerFactory, RES are modelled as harmonic sources and assigned flicker coefficients. The solar PV system was assumed to inject the current harmonic spectrum of a 0.95 MVA solar PV installation [21] shown in Table 1. The Flicker coefficients assigned are shown in Table 2.

Table 1. Injected Harmonic Current Spectrum of Solar PV.

Harmonic order (f/fn)	Magnitude %
3	1.28
5	3.78
7	1.53
9	0.38
11	0.37
13	0.37

Table 2. Solar PV System Flicker Coefficients.

	Network angle, psi deg	Coefficient, c(psi)	Stepfactor, kf(psi)	Voltage change factor, ku (psi)
1	30	0.4	0.11	0.12
2	50	0.32	0.1	0.09
3	70	0.23	0.07	0.08
4	90	0.43	0.06	0.05

2. Modelling of wind turbine generator system:

Wind turbine generator (WTG) systems operate at either fixed or variable speeds. Variable speed WTGs are the most regularly used and operate at various wind speeds [22] . This study considered a WTG system based on the doubly-fed induction generator (DFIG) technology due to its numerous advantages [23]. The authors in [24] describe the model equations for the DFIG model and its equivalent circuit.

The WTG system was modelled using the 0.69kV, 1.0MW DFIG WTG template available in the DigSILENT Power Factory library. The WTG system designed generates 0.5MW at 50Hz and unity power factor. The DFIG WTG system was assumed to inject the current harmonic spectrum illustrated in Table 3 and assigned flicker coefficients for worst-case switching as shown in Table 4 of a Vestas V90/2000kW wind turbine converters that are to be installed at Meru Wind Power Station currently under construction.

Table 3. Injected Harmonic Current Spectrum of DFIG WTG.

Harmonic order (f/fn)	Magnitude %	Harmonic order (f/fn)	Magnitude %
2	0.2	29	0.1
3	0.1	31	0.2
4	0.2	32	0.1
5	0.8	33	0.1
6	0.2	35	0.1
7	0.2	46	0.1
10	0.1	48	0.2
11	0.5	50	0.1

Table 4. DFIG WTG System Flicker Coefficients.

	Network angle, psi deg	Coefficient, c (psi)	Step factor, kf(psi)	Voltage change factor, ku (psi)
1	30	2	0.02	0.24
2	50	2	0.02	0.18
3	70	2.1	0.02	0.1
4	85	2.1	0.02	0.04

3. Modelling of biomass micro-turbine generator system:

Micro turbine generators (MTGs) burn various gaseous and liquid fuels to generate energy streams to turn electrical generators. MTGs are classified as recuperated or un-recuperated and single or two shaft models [25].

Combined heat and power installations commonly use single shaft recuperated micro turbines [26]. Micro turbine systems employ the permanent magnet generator (PMSG) technology due to their high efficiency. Moreira and Lopes [27] illustrate the dynamic model of a single shaft micro turbine engine.

In Power Factory, the MTG modelled was a combined cycle power plant developed by [28]. The MTG was configured to generate a maximum of 0.5 MW of active power at the unity power factor and 12.66 kV terminal voltages. The micro turbine generator was assumed to inject voltage harmonic spectrum based on Kramer's published test report on distributed systems integrated with a micro turbine system connected in parallel to flywheel storage [29]. The micro turbine generator system developed for this study was not assigned flicker coefficients since it was developed using the PMSG model, and it is not possible to evaluate flicker according to IEC 61400-21 standard.

IV. SIMULATION, RESULTS AND DISCUSSION

In this study, two case studies were considered. The bus and load data of the IEEE-33 bus selected for this study is found in [13]. Harmonic load flows were carried out in DigSILENT PowerFactory software using the Power Quality and Harmonic Analysis tool to determine harmonic and flicker emission levels.

The Voltage Total Harmonic Distortion

($THD_V THD_V$)

Levels obtained were compared with the IEEE 519-2014 standard, which defines limits for distribution networks. Additionally, the levels of flicker emitted were compared with the compatibility levels for flicker perceptions as defined by IEC 61000-3-7 specifications for MV and LV networks.

1. Case study 1:

In this case study, three connection scenarios were made whereby generators of the same RES type and capacity were connected to buses 6, 15 and 25 for each connection scenario to increase the penetration level of each RES type. The values of $THD_V THD_V$ and short ($Pst\,Pst$) and long-term ($Plt\,Plt$) flicker perceptions for switching and continuous operations obtained are illustrated by Figures 1 and 2, respectively. From the simulated results, the levels of $THD_V THD_V$ were within the 5% limit set by the IEEE 519-2014 standard for MV networks. Additionally, the level of $THD_V THD_V$ increased with increased penetration of each RES type. The lowest level of $THD_V THD_V$ at Points of Common Coupling (PCC) were obtained when Solar PV was connected to bus 6 and the highest when microturbine generators were connected to buses 6, 15 and 25. The measured levels of flicker perceptions ($Pst\,Pst$ and $Plt\,Plt$) were also found to be within the 1.0 and 0.8 compatibility levels for $Pst\,Pst$ and $Plt\,Plt$ as defined by IEC 61000-3-7 specifications.

The DFIG WTG system emitted higher flicker levels than Solar PV during continuous operations, whereas the Solar PV emitted higher flicker levels than DFIG WTG during switching operations.

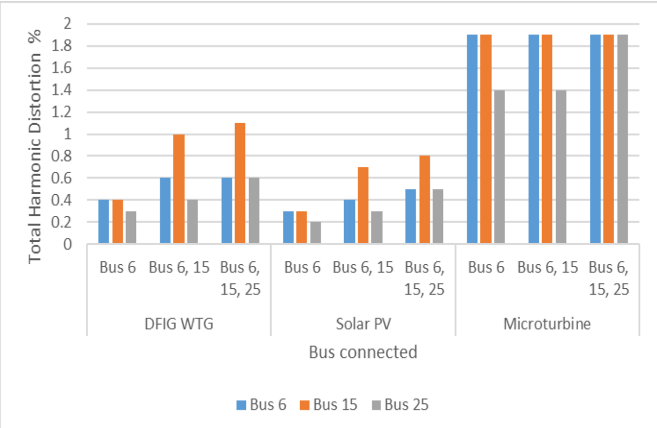

Fig 1. THD (%) at PCC after integrating RES of same type and capacity (increasing penetration level).

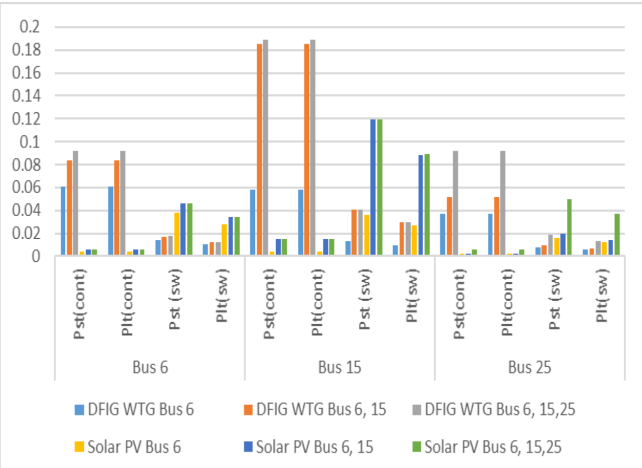

Fig 2. Short and Long-term Flicker Perceptions for Switching and Continuous Operation.

2. Case Study 2

In this case study, the DFIG WTG, Solar PV and microturbine generators of equal capacity were connected interchangeably at the selected buses in six different combinations, as illustrated by Table 1. The values of THD_V THD_V and short (Pst Pst) and long-term (Plt Plt) flicker perceptions for switching and continuous operations obtained are illustrated by Figures 3 and 4, respectively. The highest level of THD_V THD_V was obtained in the sixth combination and the lowest in the fourth combination from the simulated results.

The levels of THD_V THD_V emitted in all the six combinations were within the 5% limit set by IEEE 519-2014 standards. Comparing the THD_V THD_V results for the first and second case studies, connecting the micro turbine generators in all the three selected buses at the same time (case study 1) produced higher THD_V THD_V than any combination of case study 2. This can be attributed to the micro turbine's generating system inverter characteristics that make it emit the highest levels of THD_V THD_V compared to the inverters used for the DFIG WTG and Solar PV systems.

Additionally, connecting the Solar PV system in all the three selected buses simultaneously (case study 1) produced lower THD_V THD_V than any combination of case study 2. This can also be attributed to the Solar PV system inverter characteristics. The flicker levels emitted in all the six combinations were within the 1.0 and 0.8 compatibility levels for Pst Pst and Plt Plt as defined by IEC 61000-3-7 specifications.

Table 5. RES combination for case study 2.

RES Combination	Bus 6	Bus 15	Bus 25
1	Solar PV	DFIG WTG	Microturbine
2	Solar PV	Microturbine	DFIG WTG
3	DFIG WTG	Solar PV	Microturbine
4	DFIG WTG	Microturbine	Solar PV
5	Microturbine	Solar PV	DFIG WTG
6	Microturbine	DFIG WTG	Solar PV

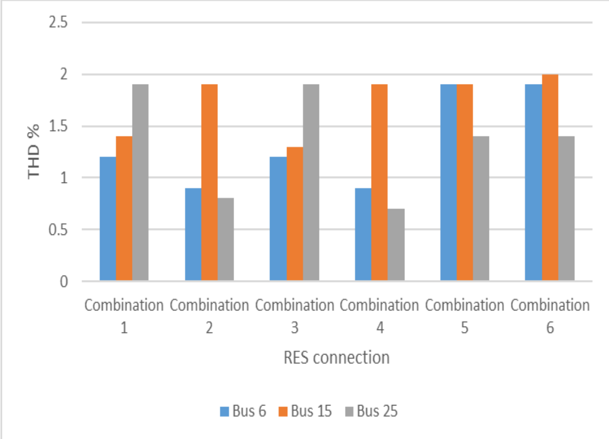

Fig 3. THD (%) at PCC for the six combinations.

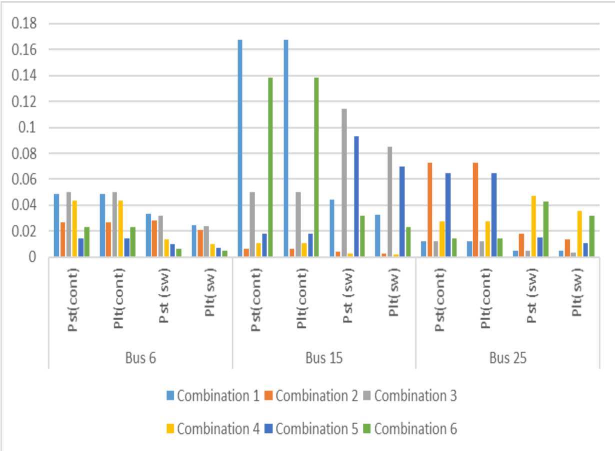

Fig 4. Short and Long-term Flicker Perceptions for Switching and Continuous Operation for the six combinations.

V. CONCLUSION

This paper examined the impact on harmonics and flicker of low voltage (LV) and medium voltage (MV) networks caused by the integration of solar, wind and gas micro-turbine generators. This was realized by integrating the RES at selected locations of the IEEE-33 bus system and carrying out harmonics and flicker analysis using DigSILENT Power Factory software. From the simulated results, the levels of harmonic distortion and flicker levels on the IEEE 33 bus system increased due to the integration of RES.

Additionally, the results indicate that the levels of THD_V THD_V and flicker perceptions (Pst Pst and Plt Plt) emitted is dependent on the type, location, penetration level and whether a single-type of RES or combination of RES was installed. The measured levels of THD_V THD_V and flicker perceptions (Pst

Pst and $Plt\,Plt$) were also found to be within limits prescribed by the IEEE 519-2014 and IEC 61000-3-7 standards.

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