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A comparative analysis of constant impedance and constant power loads in a distribution network

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ABSTRACT

Most conventional power systems adopt radial distribution network wherein multiple loads are connected across the distribution transformer. As the number of loads increases, it results in poor voltage profile at the distant receiving end reducing power delivery. This issue worsens with the large-scale influx of electric vehicles and power converter-fed loads, which draw constant power irrespective of supply voltage. Such loads exhibit negative incremental resistance behavior and also have a dynamic response which affects the network in a manner different from constant impedance loads. This paper compares the effects of constant power and constant impedance loads by modeling adjustable converter dynamics for constant power loads. It analyzes line currents, load voltages and power transmitted in a four-load radial test system with optional distributed sources. Results show poorer voltage profile and the effect of power converter dynamics in constant power loads compared to conventional loads. Adding distributed sources improves voltage profile considerably, and transmission losses are reduced. Steady state analysis is then extended to an IEEE 31-bus 23 kV distribution test system with similar results. Transmission losses are computed along different branches, and the influence of loads and sources are analyzed. The outcomes of the analysis can be used in arrival of loss allocation in a system where peer to peer energy sharing is envisaged.

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1. INTRODUCTION

Energy supplied by the utility, which in many cases is largely from fossil-fuel-based generation, causes carbon emissions and requires large scale infrastructural upgradation to keep up with the rising energy demand if the centralized generation, transmission and distribution model is used. Hence utilization of distributed renewable energy sources such as solar and wind is gaining importance due to reduced environmental impact [1]–[3]. This has led to a more decentralized, deregulated energy market and the possibility arises wherein customers can locally share energy between themselves.

Integration of plugin electric vehicle (PEV) is increasing as it reduces fuel cost per distance traveled and greenhouse gas emissions if energy is sourced from renewables [4], [5]. The number of electric vehicles (EVs) on-road worldwide surpassed 10 million in 2022. Energy consumption of a PEV for driving is around 0.2 kWh/km [6]. Assuming half of the EVs are on-road driving an average distance of 40km per day, daily worldwide energy consumption of EVs is around 40 GWh. But delivering 40 GWh in low voltage distribution networks is a big challenge if the charging is not coordinated, considering the shortfall of power [7]. The growing number of EVs will lead to a significant increase in power demand that can overload the current grid infrastructure during peak hours [8]. This unusual surge in power demand highlights the importance of exploring more sustainable energy resources and enhancing the grid infrastructure to accommodate it [9]. The rise in PEV adoption will lead to a shift in the power system's characteristics, transitioning from constant impedance loads (CIL) to constant power loads (CPL) [10]. These new loads are inherently unstable and can pose a risk of grid failure if not properly managed [11]. In addition, most of today's appliances have power-electronic based converters which are tightly regulated in order to deliver constant power [12]. Hence, more of the loads today are constant power loads. As most of our power systems are radial in structure, loading effect at the farthest receiving end due to loads upstream will be the highest which results in low voltage profile compared to utility side of the system [13], [14]. By adding distributed generating sources, voltage profile is improved, and transmission losses are reduced [15]–[17]. The decentralized coordination of energy producers and consumers at the local level, operating independently without the need for centralized operators is termed peer-to-peer energy sharing. This system provides two-way communication and energy flow between local prosumers [2]. With proper energy trading mechanisms there will be better local power and energy balance.

An alternative for large scale changes in distributed network and the environmental effects would be to have consumers generate their own energy for charging PEVs and any excess/deficit can be managed by adopting the prosumer model (certain consumer becoming energy producer) [18], [19]. Here, the customers actively purchase and sell energy at prices determined by the market. Energy bidding marketplaces, where participants strategically submit offers to buy or sell energy, are the heart of this process [19], [20]. By means of this method, customers can directly influence and respond to the current market conditions, tailoring their energy buying strategy to accommodate their own needs. Another important component of energy sharing is bilateral contracts, which give customers a more direct and individualized way to manage their energy transactions. These contracts create a framework that is tailored to the particular needs and preferences of the entities involved by allowing them to mutually agree on terms for the purchase or sale of energy. This direct engagement between consumers facilitates a more flexible and dynamic energy market, fostering efficiency and responsiveness to changing demands. These models exhibit reduced transmission losses and are resistant to disruptions. Having generating sources such as solar photovoltaic panel, wind resource along with storage devices can help maintain voltage profile and reduce transmission losses. But each energy transaction must be recorded to allocate the losses contributed by each load [4]. To avoid over estimation of losses, a method where losses are normalized and reflects the effect of network parameters, penalty/compensation for energy imbalance due to difference in scheduled energy and actual energy transaction must be considered. So, energy sharing between prosumers who have local generation will be the optimal way to enhance power quality, improve overall efficiency and reduce the need for large scale restructuring of the power system to meet increased demand due to increased PEV penetration besides being economical to the consumers of distribution system [21], [22].

Dynamic models are used for their ability to model both transient and steady state conditions. An overview of the compensating techniques utilized to maintain stability was presented in [23], which develops nonlinear state space model of DC and AC microgrids with constant power and constant voltage loads. This paper compares the dynamic behavior of constant power loads and constant impedance loads on a test system, by developing a novel control model of a constant power load considering transmission line resistance and inductance. The comparison is then extended using steady state analysis for the two classes of loads, on a larger IEEE test system. Variations in transmission losses, voltage profile and line currents in the transmission line are analyzed. Simulations show the greater influence of constant power loads on line losses. Finally, Bialek's electricity tracing method is applied to trace the flow of power so that consumers and/or generators are charged with respect to their transmission loss allocation.

2. TRANSMISSION LINE MODEL

A radial short transmission line model is considered since the length of the line is limited. The shunt reactance is neglected due to its low leakage current in such a line. The equivalent of a finite length transmission line with n number of consumers/nodes in a distribution system is shown in Figure 1. Each line has a resistance R and inductance of L. Parameters for all the lines are considered the same for convenience. V_S is the sending end voltage, V_R is the receiving end voltage, $V_1, V_2, \dots V_n$ are the node voltages. Moving away from the source, the load voltage decreases due to voltage drop in each line. Hence the voltage in the last node will be the least. Line current in the node decreases moving away from the source as the loading in the node keeps reducing. This variation is shown in Figure 2. Adding another generating source near the last load will improve the voltage profile and reduce line currents as shown in Figure 3. Hence total transmission loss in the system is reduced. This model considers a distribution system with 4 consumers. Distribution transformer is the source at the sending end. The loads considered here are of constant impedance load type having resistance of 17.33 ohms each (Assuming nominal power demand of each consumer to be 3 kW). Each of the consumers are connected via the transmission line which is modelled as short transmission line as the length is typically less than 50 m. A second source is added at the node present in extreme opposite end of the first generating source.

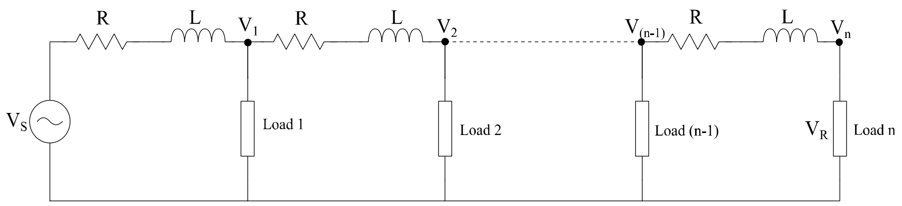

Figure 1. Equivalent circuit of distribution network of finite length with ‘n’ loads

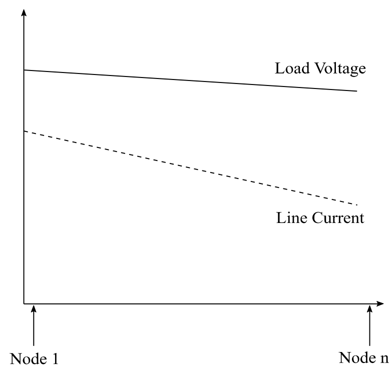

Figure 2. Variation of voltage profile and line currents at different load points with a single source

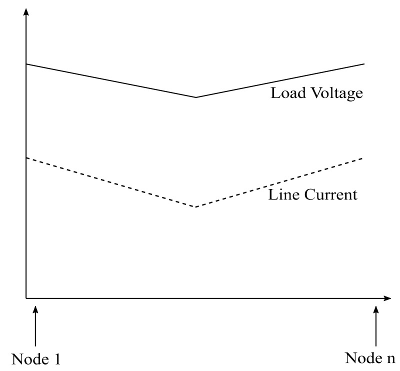

Figure 3. Variation of voltage profile and line currents at different load points with two sources at either end

3. CONSUMER LOAD MODEL

A typical residential load consists of heating, lighting and other rotary appliances. These have variable power consumption based on terminal voltage. Constant power loads are mostly used in commercial applications such as industrial manufacturing, testing units, stable power supplies for data centers and PEV charging stations and certain domestic appliances [24]. In this paper, two types of loads are considered: constant impedance loads representing residential loads and constant power loads representing PEV charging stations in residential areas.

3.1. Constant impedance loads

Electrical loads that maintain constant impedance regardless of the variations in voltage or current are said to be constant impedance loads. Its ratio of load voltage to current remains constant.

$$z = \frac{v}{i} = constant \tag{1}$$

3.2. Constant power loads

Constant power loads are those that consume a constant amount of electrical power regardless of variations in supply voltage. A typical voltage versus current graph of a constant power load is shown in Figure 4. Because line current near the source is the total of all load currents, it has the largest value while bus voltage is at its peak near the generator and decreases moving away from the generation. Instantaneous impedance $(\frac{v}{i})$ of the constant power load is positive. Whereas its incremental impedance $(\frac{\Delta V}{\Delta I})$ is negative which makes the system unstable [11]. i.e., any increase or decrease in voltage of CPL, there will be decrease or increase in the current respectively. This has a destabilizing effect in the system [23]. The block diagram of constant power load model along with transmission line is shown in Figure 5. P_n* is the reference power, e is the error signal, u is the control output of PI controller, R_{load_ref} is the reference load resistance, R_{load} is the load resistance, R and L are transmission line resistance and inductance, i_{Ln} is the current flowing in the load, i_n is the line current, v_n is the voltage across load and P_n is the instantaneous power. Subscript $n, n-1$

and $n + 1$ indicate the node considered, previous node and next node respectively. The PI controller receives the error signal resulting from the variation between the reference power and the derived power. To obtain the control signal u, proportional and integral gains (K_p and K_i) are tuned. Ratio of load reference resistance (R_{load_ref}) to u gives instantaneous current i_{Ln} from which power P_n is derived. Line current i_n is derived by applying Kirchhoff's current law; node voltage v_n is derived by applying Kirchhoff's voltage law. Figure 6 depicts a model block of CPL based on the model displayed in Figure 5.

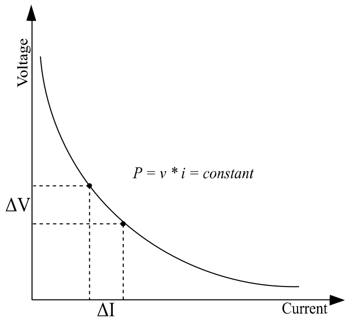

Figure 4. Voltage versus current graph of constant power load

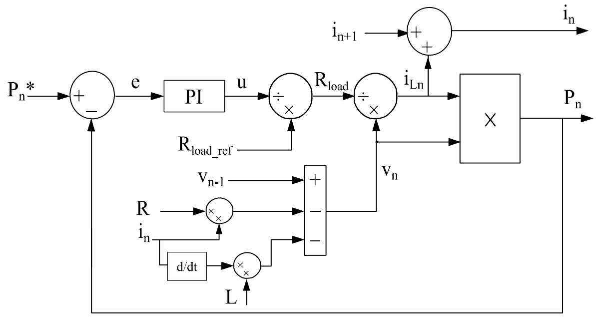

Figure 5. Block diagram representation of constant power load model along with transmission line

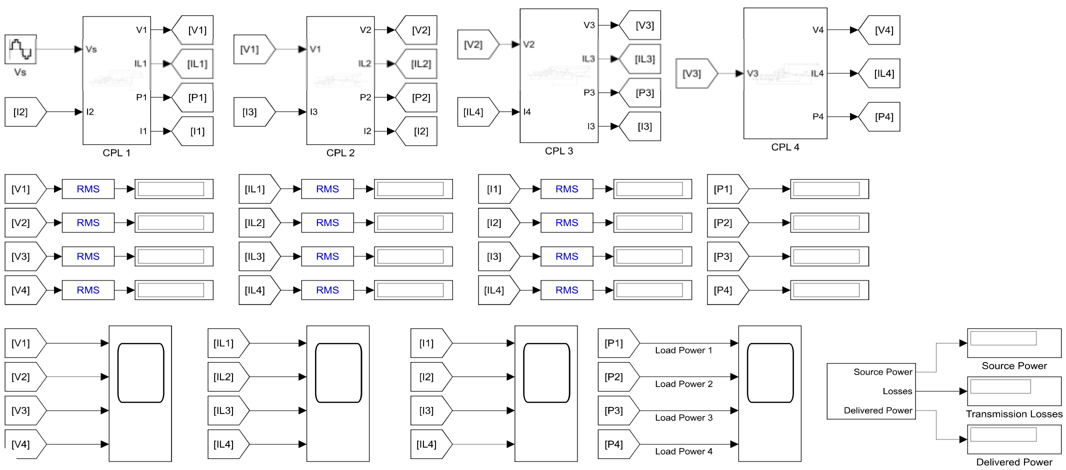

Figure 6. Simulink model of system with 4 CPLs connected via transmission lines in an AC microgrid

4. SIMULATION MODEL

Simulation is carried out in MATLAB/Simulink software using sim-power system tools. Multiple loads are connected to generator via distribution transformer. Parameters used for simulation are shown in Table 1. Simulation is run and steady state analysis of system is studied.

Table 1. Parameters used in simulation

Parameter	Value
Sending end voltage	230 V, 50 Hz
Consumer load	3 KW each
Transmission line	0.02 Ω, 40 μH
K_p, K_i	0.00005, 0.01

4.1. System with constant impedance load

This system considers a single-phase alternating current (AC) distribution system with a source of 230 V, 50 Hz with four constant resistance loads of 17.6333 Ω each. Power consumed by each load is

2,973, 2,953, 2,939, and 2933 W. Total transmission loss in the system is 100 W. By the addition of generating source at the far end, power consumed by each load is 2,986, 2,980, 2,980, and 2,986 W. Total transmission loss is 33 W.

4.2. System with constant power load

With the electrification of home appliances and vehicles, the increase in number of loads interfaced via tightly regulated power-electronic converters, draws constant power regardless of the applied voltage. Hence there is a large percentage of CPLs in modern power systems [25]. Figure 6 shows the Simulink model of the system connected with 4 individual model of CPLs of Figure 5 (refer Figure 1). Here the power delivered to the load is maintained constant. Total transmission loss in the system is 104 W.

Additional generating source is added at the extreme opposite end of the first generating source. This ends up reducing total transmission loss in the system to 34 W. Figure 7 shows steady state line current and load voltage at different load points in different cases.

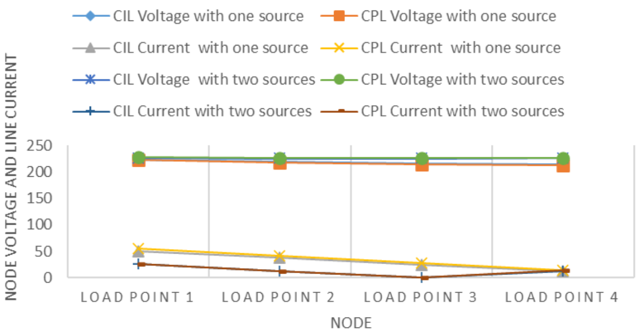

Figure 7. Variation of line current and load voltage at different buses

A sudden voltage changes from 230 to 250 V and to 220 V is simulated to validate the CPL. It can be observed that the power delivered to the loads remains constant even with the variation in input voltage. Figures 8 and 9 show the dynamic response of system with CIL and CPL respectively. At 0.3 and 0.6 s there is a change in voltage. CIL will adjust its power to maintain its impedance constant. Whereas CPL retains its power across the load even after disturbance [26]. Figure 10 shows the real-time load demand of four consumers. Its corresponding load voltage and line current are shown in Figures 11 and 12.

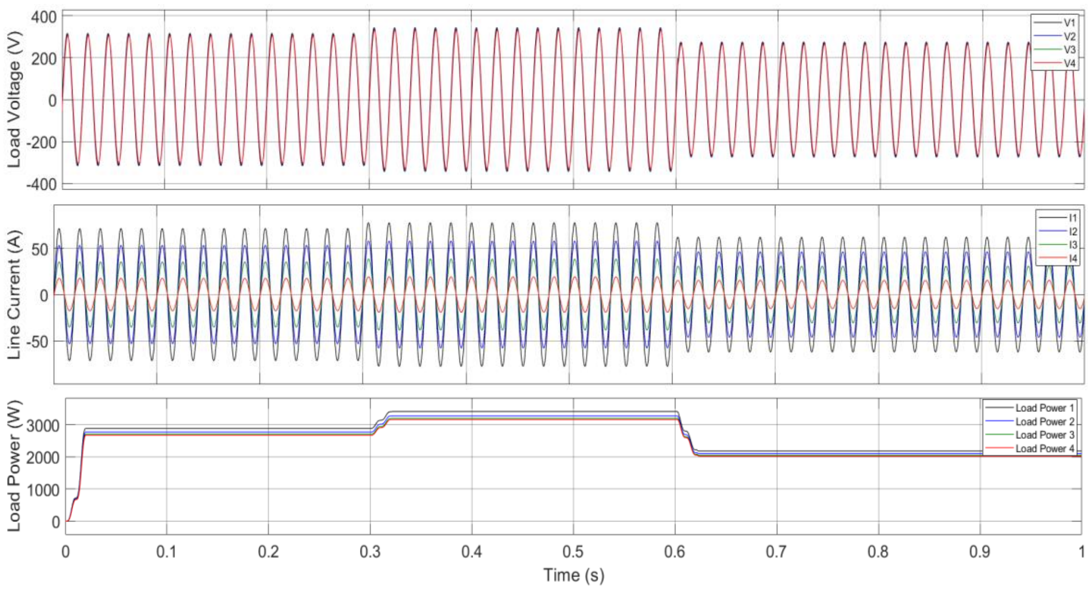

Figure 8. Load voltage, line current, load power of CIL

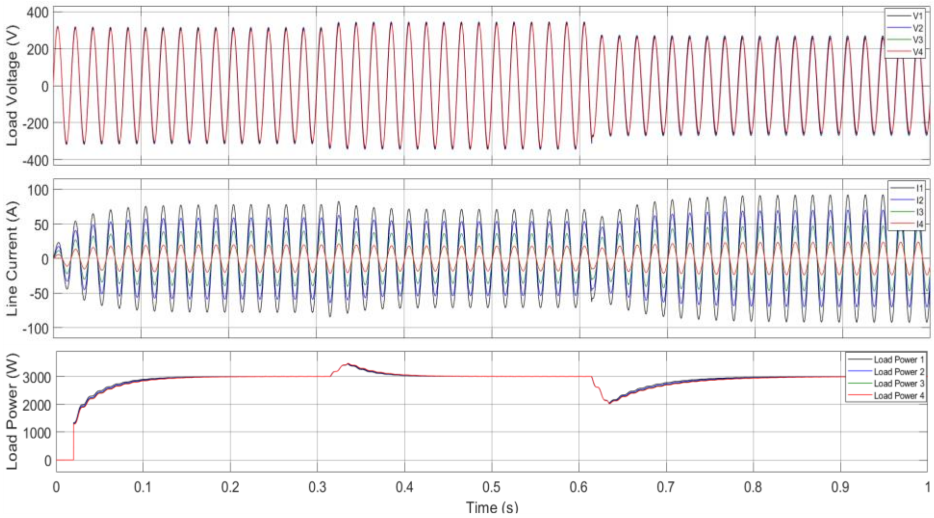

Figure 9. Load voltage, line current, load power of CPL

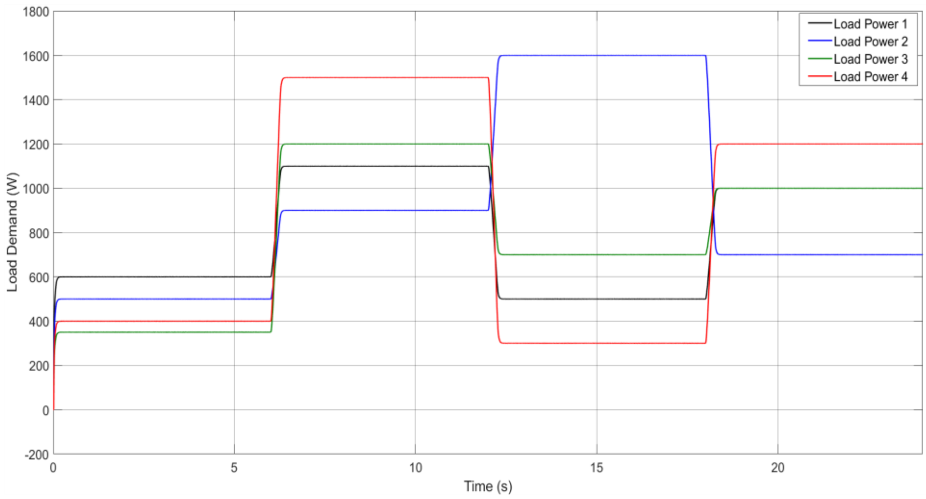

Figure 10. Load demand of consumers

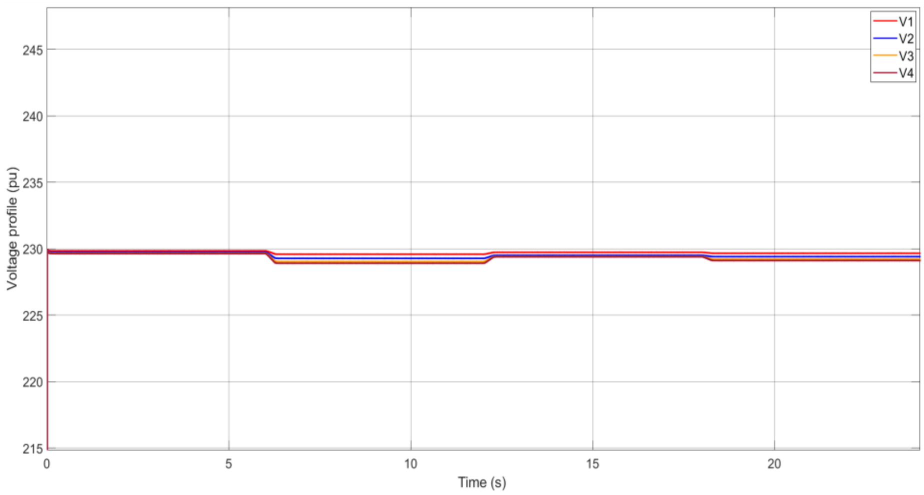

Figure 11. Voltage profile at the consumer end

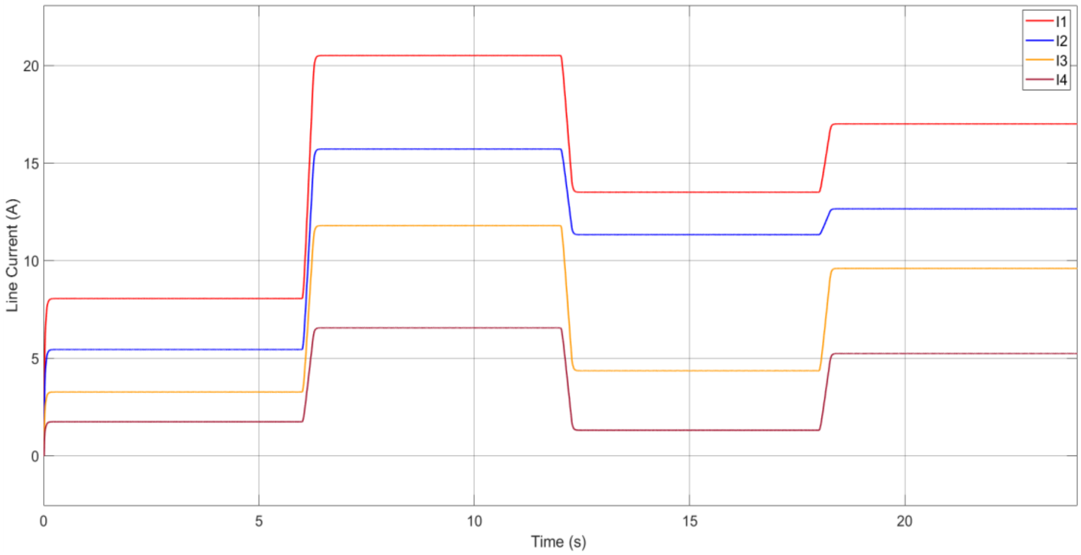

Figure 12. Line currents

5. LOAD FLOW STUDY

Simulation of IEEE 31 bus 23 kV distribution test system is considered to evaluate the voltage and power losses in the system. The system has 22 buses each having 53 residential loads (R1-R53) [9]. Load flow study is carried out in a part of the system having one distribution transformer followed by 52 residential loads as shown in Figure 13.

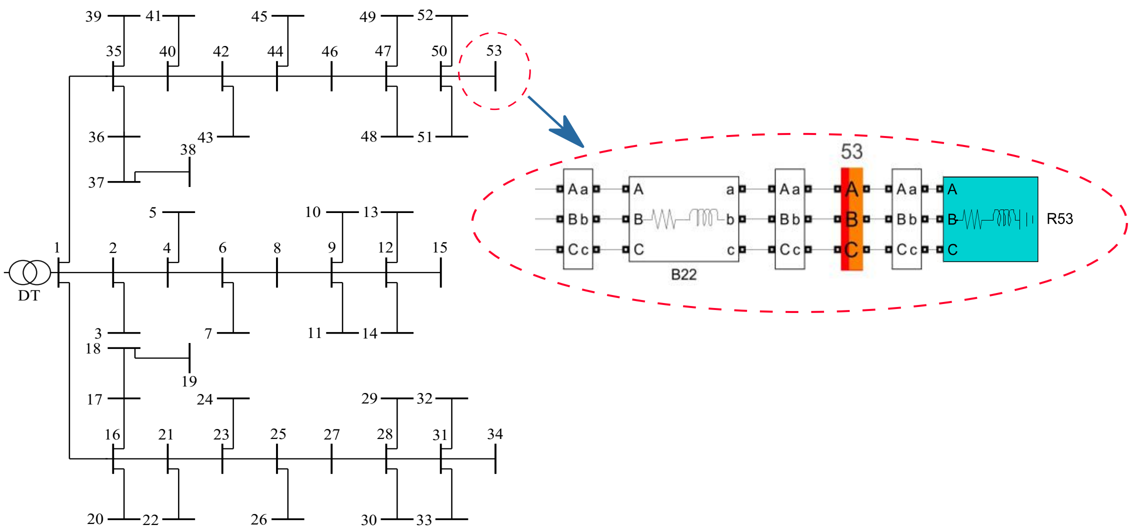

Figure 13. Single-line diagram of residential 415 V distribution network

Residential loads are linear loads of 1.5 kW at unity PF each. 26 PEV chargers of 4 kW are added at a few residential loads. Load flow in the first case considers all loads to be constant impedance load type. In the second case, residential loads are modelled as constant impedance loads and PEV chargers as constant power loads [27]. In the third case, generation sources are added in a few buses (node 15, node 27, node 46, and node 53). Load specification is given in Table 2. Figure 14 shows the result of the load flow carried out in three cases. One can note that instances of voltage violations occur more frequently and are more impactful when the loads are of the CPL type underscoring the critical need to prioritize power quality as the number of EVs increases.

Table 2. Load data

Node	Type of Load	Power	
		W	Var
R2 – R53 residential loads	CIL	1,500	0
PEV chargers	CPL	4,000	0

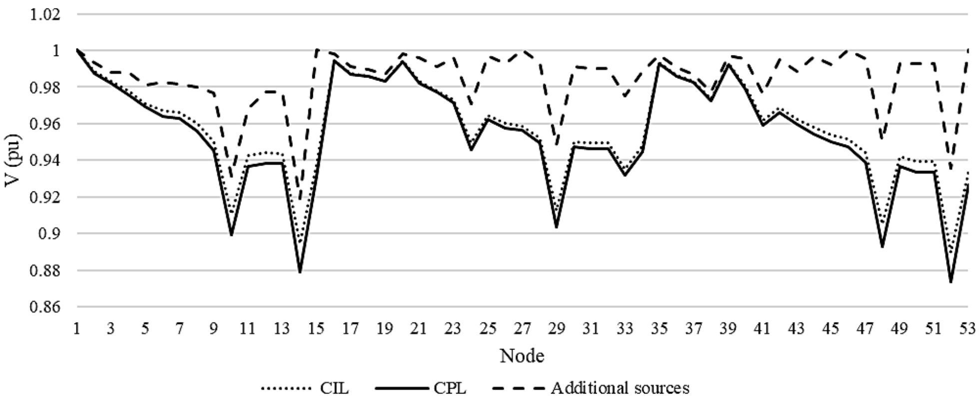

Figure 14. Voltage profile with CIL, CPL, and addition of sources

6. ALLOCATION OF TRANSMISSION LOSSES

Bialek's power tracing with gross power flow using upstream-looking algorithm is used here to allocate total transmission loss in each generator and loads [28]. According to Bialek [28], Gross nodal power at node i can be written as (2)-(6):

$$\left[P_i^{gross}\right] = \sum_{j=\alpha_i} \frac{[|P_{j-i}|]}{[P_j]} \left[P_j^{gross}\right] = [P_{Gi}] \tag{2}$$

$$[A_u][P^{gross}] = [P_G] \tag{3}$$

$$[A_u] = \begin{cases} 1 & ; \quad if\ i = j \\ \frac{-[|P_{j-i}|]}{[P_j]} & ; \quad if\ j \in \alpha_i \\ 0 & ; \quad otherwise \end{cases} \tag{4}$$

$$\left[P_{Li}^{gross}\right] = \frac{[P_{Li}]}{[P_i]} \left[P_i^{gross}\right] \tag{5}$$

$$[ld] = \left[P_{Li}^{gross}\right] - [P_{Li}] \tag{6}$$

where $|P_{i-j}|$ is the line power flow from node i to j; P_j and P_j^{gross} are the nodal power flow and gross power flowing through node j; P_{Gi} is the generation at node i; n is number of nodes, α_i is the set of nodes supplied directly from node i; Au is a $n \times n$ upstream distribution matrix; P_{Li} is the actual demand in node i; P_{Li}^{gross} is the gross demand in node i; ld is the loss distribution matrix where transmission loss is allocated to individual loads.

Load flow carried out to the system with PEV's of CIL type lead to a total transmission loss of 2738.37 W and with PEV's of CPL type lead to a total transmission loss of 3292.13 W. Figure 15 shows the comparison of loss allocation with CIL and CPL based on Bialek's method. It is observed that loads near to the generation have lower transmission loss compared to loads which are far away from generation. This becomes a critical point when there are multiple transactions of power between the users in the distribution network [25]. Hence a normalizing factor of losses must be included to compensate for the over estimation of electricity bill. Further it is observed that transmission loss in the system is reduced to 1162.38 W when generation sources are added in between the system. Table 3 gives a clear picture of how losses are affected with generation and loads.

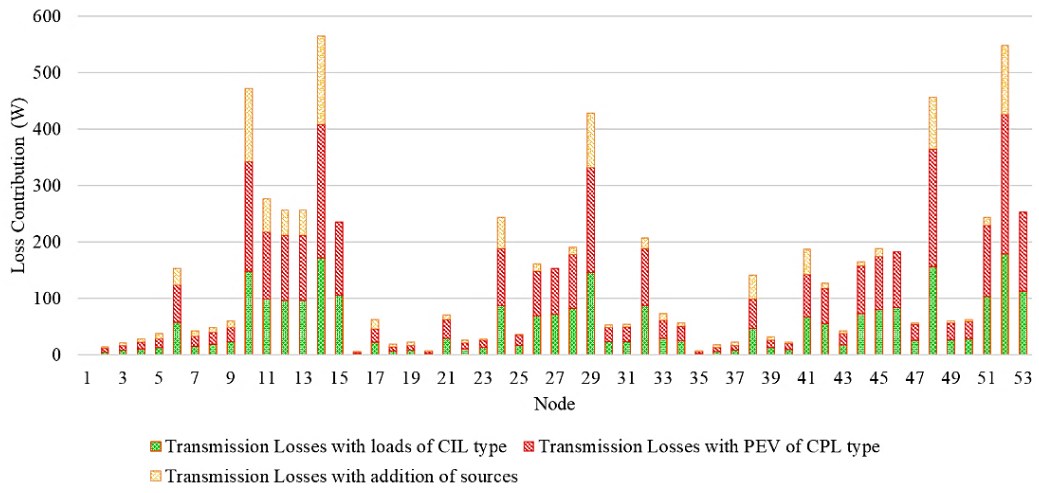

Figure 15. Comparison of loss allocation with loads of CIL type, PEV of CPL type and with addition of sources

Table 3. Comparison of transmission losses with generation and load

Cases	With loads of CIL type	With PEV of CPL type	With additional sources
Power consumed (Watts)	57712.76	61635.89	61017.85
Load power (Watts)	54974.39	58343.76	59855.47
% of loss	4.7448%	5.3413%	1.9049%

7. RESULTS AND DISCUSSION

Steady state results are compared with system having constant impedance loads and constant power loads. When the system has constant impedance loads, it is observed that voltage at the load points decreases going far away from generating source. Hence the voltage at the receiving end of the distribution system will be the least which affects the power delivered to the loads at the receiving end. Line current flowing in the transmission line near to the generation is higher when compared to the line currents going far away from the generation. The same system having constant power loads will have much higher transmission line current and voltage drop and when compared to the previous case. Node voltage dropped below standard voltage limit of 0.9 pu can be observed in Figure 14. Hence, it increases overall transmission loss [24]. Adding more source of power such as renewable energy source or power converter fed battery powered converter at the receiving end, reduce voltage drop across load points with overall reduction in transmission losses. This can be observed in Figure 14 that node voltages are within the standard voltage limits when additional sources are added. Line currents in the transmission line are also much less compared with single generation.

Bialek’s power tracing method is used here to allocate losses contributed by each load with respect to the generation. The contribution of a load to transmission loss is less when the load is closer to the generation (refer Figure 15). This is an important consideration if energy is to be shared between a pair of prosumers although in conventional distribution, losses are apportioned equally irrespective of contribution of a load to overall losses.

8. CONCLUSION

Single-phase AC system with multiple loads connected via transmission lines are analyzed in this paper. It is observed that constant power loads lead to higher voltage drops and losses compared to constant impedance loads. It also affects the system dynamics and could potentially lead the system to instability. The dynamic model developed can be used to study the effects of load dynamics which can be altered to make individual loads. Load flow analysis is carried out to determine loss in the system. Energy sharing between the customers helps to avoid voltage-drop and minimize transmission power loss in a radial distribution network. Consumers who have renewable energy or battery storage may become producers based on their energy availability. This would also greatly enhance the power handling capacity of the network.

In certain lines, energy sharing results in greater energy transmission than in others. In the prosumer model, computation and allocation of losses is important for matching energy and billed usage, and this has also been analyzed in the paper. As a result, allocating the losses becomes crucial to the billing process. Thus, the analysis came out in this paper can be extended to optimize and cost energy transfer between peers.

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