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Evaluating the Impact of Tie-Point Controllers on the Distribution Grid

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SUMMARY

Electric distribution grids in the US are commonly operated radially, where power flows from the feeder head down to customer while tie points between feeders provide some flexibility to the distribution operators to shift demand from one feeder to another. Reconfiguring these tie-points to shift demand can either be done for addressing feeder conditions or as a temporary solution to a fault on the system. However, the amount of power shifted between feeders is dependent on the conditions of the grid, while the frequency of these load transfers is minimized to avoid customer service disruption.

Tie-point controllers are power-electronic-based devices that enable the utility to throttle power from one feeder to another without creating a loop in the system. The amount and direction of the real and/or reactive power transferred between feeders can be controlled to achieve a specific objective either through a local discrete controller or through SCADA by the system operator. As a result, the benefit and impact of a tie point controller device will depend on the specific application and specific scenario in which it is implemented.

This paper explores the functionalities and impact of a tie-point controller on electric distribution systems through various distribution planning studies in terms of mitigation of thermal and voltage violations, energy efficiency and other metrics. These studies are performed with time-series simulation to evaluate the benefits of different tie-point controller controls.

KEYWORDS

Tie-Point Controller, Non-Wire Alternative (NWA), Power Electronics, EV Integration, Capacity Deferral

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INTRODUCTION

Growing adoption of electrification technologies such as electric vehicles and heat pumps has pushed the electric distribution industry to adapt their conventional planning practices and consider the deployment of smart grid devices to improve system flexibility and increase utilization of existing infrastructure. The adoption of these electrification technologies may not always be uniform from one distribution feeder to another. Depending on customer behaviour, some distribution feeders could quickly approach their operational limits due to higher adoption levels while others could still have significant unused capacity.

Electric distribution systems in the US are generally operated radially, where the power flows from the feeder head down to the customer in a radial fashion. The purpose of operating feeders in that fashion, amongst other benefits, has been to simplify the coordination of protective devices to easily isolate section of a fault on the feeder. Although feeders operate radially, normally-open tie-points between distribution feeders can be leveraged to reconfigure the system and shift sections of a feeder from one feeder to another. Reconfiguring normally-open and normally-closed switches to shift demand from one feeder to another whenever capacity is available can either be done for addressing feeder conditions or as a temporary solution to a fault on the system. However, the amount of power shifted between feeders is dependent on the configuration of the system.

Distribution feeder reconfiguration (also referred as load transfers) is an effective way to manage load growth wherever there is available capacity across multiple adjacent feeders. However, this is often a static change to the system that distribution planners leverage during their planning cycle where some feeders can experience repeated reconfigurations year after year in some high load growth areas. Frequent reconfigurations on the same feeder are obviously something distribution planners aim to avoid to limit disruption to the customer but these transfers are often constrained to the topology of the feeders and the location of switches / reclosers. Moreover, a static load transfer may limit flexibility in system operation and result in under-utilizing some of the capacity in the system because of the inflexibility in the amount of power transferred from one feeder to another. One alternative to a load transfer via a recloser or manual switch is a power-electronic based smart-grid device that would enable to throttle the power from one feeder to the next without creating a loop in the system. The amount and direction of the real and/or reactive power transferred between feeders can be controlled to achieve a specific objective either through a local discrete controller or through SCADA by the system operator. This paper explores the technical value and the impact that a tie-point controller can provide to distribution systems.

Although it is not a common mitigation solution in the US, the concept of controlled power flow across two distribution feeders has already been discussed in literature under different terms: loop power controller (LPC), loop power flow controller, unified power flow controller (UPFC), etc. [1-10]. The majority of the literature discusses the use of tie-point controllers to reduce the aggregated power losses (e.g. I^2R) by actively controlling the real power flow between the two feeders [1,2,4,6,7,8,9,10]. Controlling the reactive power injection of the tie-point controller can also independently provide some level of voltage regulation, whether it is to avoid over or under-voltage conditions on the system [1,4,7,8,9]. The literature also discusses leveraging a tie-point controller to balance thermal loading of distribution feeders to defer capacity investment [3,5] and to improve system reliability [6, 10]. A tie-point controller can provide benefits to distribution feeders as a non-wire alternative (NWA) solution as well as a mitigation solution to integrating distributed energy resources (DER): solar PV impacts [1,3,5] or energy storage integration [10]. Finally, the impact of tie-point controllers on networked[1] distribution feeders is also discussed as a way to control the power flow through a meshed distribution network to reduce system power losses and to regulate voltages [2, 8].

Because the technical value and impacts of a tie-point controller are specific to a location and the way the device is operated, this paper presents a methodology to assess the effect of a tie-point controller on distribution systems for electric utilities to leverage in their planning process. The technical value assessment is performed by evaluating the benefits: capacity deferral, distributed energy resources (DER) and electric vehicle (EV) integration, mitigation of thermal and voltage violations and other metrics capturing feeder operating conditions. Several studies were performed including time series simulation, load growth and system reliability assessment. Because the impact of a tie-point controller is multi-faceted, a Key Performance Indicators (KPIs) table was used to summarize different metrics from the time-series simulations including real and reactive power losses, impacts on other controllable elements in the system, voltage conditions, thermal loading of equipment, etc.

The rest of this paper is organized as follows. The modelling and simulation methodology is proposed in the following section. The modelling and simulation assumptions for the use-cases are discussed subsequently. The simulation results for each use-case as well as a KPI table is presented in the simulation results section. Finally, the discussion on how a tie-point controller generally affects a feeder is presented to help electric utilities identify locations with higher potential value across their territory.

METHODOLOGY

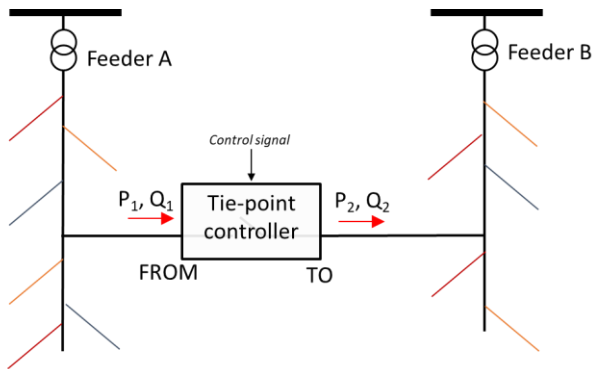

Figure 1: Dynamic tie-point controller configuration

Tie-Point Controller

The tie-point controller capabilities are evaluated by connecting two feeders at identified locations to shift power from one feeder to another while undergoing different conditions (see Figure 1). The tie-point controller model utilized for this work is provided and created by Switched Source, LLC. This model is used to represent their power electronic device, the Tie Controller. The inputs to the model of the tie-point controller consist of:

- Thevenin equivalent short circuit resistance and inductance (Ω and H) at buses of interconnection (from feeders A and B), which is used in the internal controls of the device to consider how the device would respond at a specific location in the field.

[1] Networked systems or looped systems refer to distribution systems with normally-closed tie points where nodes are energized by two or more sources simultaneously. In contrast, radial systems refer to feeders with single power sources (single feeder head).

- Phase voltage and angle (V_{ln}, rads) at buses of interconnection, which affects the operation of the power electronics in the device in terms of real and reactive power output.
- Control side: side from which to maintain the specified power transfer.
- Desired power (W, Var) transferred from one feeder to the other.

The outputs of the tie-point controller consist of real and reactive power along with the device real power losses.

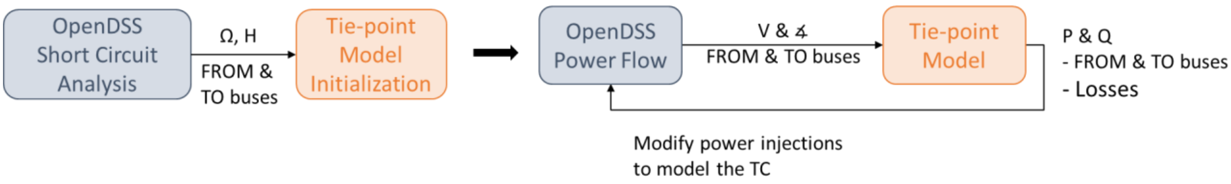

Figure 2: Convergence method

Power Flow Simulation

Due to the model's dependency of short circuit impedances and voltages at both points of interconnection, these values are obtained from the short circuit analysis and power flow solutions. The short circuit analysis provides the values necessary to initialize the tie-point model (Thevenin equivalent of the short circuit Ω and H at both connection buses). Once the model is initialized the power flow simulation can be executed in OpenDSS through its Python interface [11]. The output of tie-point controller model (provided by Switched Source, LLC) is modelled as power injections – negative or positive depending on the side of the device. An iterative process is used between the power flow solver and the tie-point controller model since the voltage conditions on the feeder determined through the power flow computation will affect the output of the tie-point controller and the power injection of the tie-point controller will affect the power flow results. This convergence method is similar to how smart inverters are modelled in power flow software like OpenDSS [12]. Convergence is obtained when there is not significant change in the circuits' bus voltages ($\Delta V < 0.001$ p.u.) after each iteration, provided the requested output power is within the range of operation of the model given the feeder conditions.

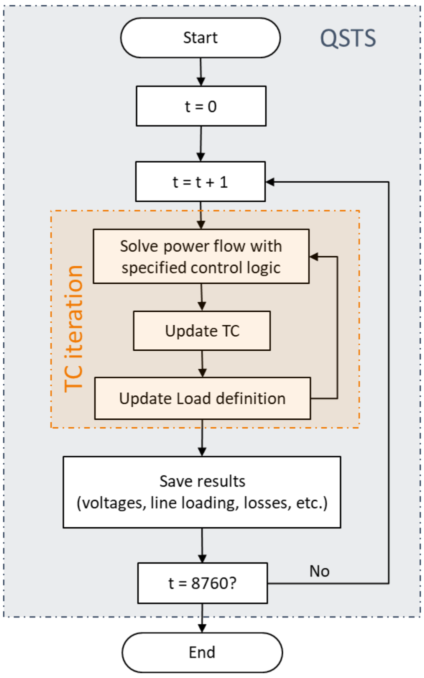

Figure 3: Time-series simulation

Because of the dynamic nature of the device, a time series simulation is necessary to study the impact of the tie-point controller operation throughout the year as the demand varies on each feeder. Thus, it is important to model the temporal behaviour of the demand on each profile using metering data (e.g. SCADA or AMI data based on availability [13]). Furthermore, any distributed generation (i.e. PV systems) or specific types of loads (i.e. electric vehicles) could also be modelled independently to further improve the accuracy of the temporal behaviour of the system. A quasi-static time-series simulation (Figure 3) where a power flow is computed at each timestep can assess how a device would operate not only under different load conditions but also consider any type of hysteresis in the controller logic used to operate the device. The static power flow logic in which the tie-point controller and the power flow solutions iterate until convergence, is applied for each time step. Various metrics such as nodal voltages, line loading, losses and power transfer are extracted at each time step.

Use Cases

Provided a specific use-case with two distribution feeders, the impact of a tie-point controller can still vary significantly depending on how the device is operated. In this paper, three scenarios are considered to demonstrate how different controller logics can impact the system.

- In the base-case scenario, the time series simulation is executed without the operation of the tie-point controller. The base-case captures the severity of issues on either system during their normal yearly operation and it's used as a reference to understand any benefit the tie-point controller can provide.
- The peak-shaving logic scenario monitors the highest loaded line in one circuit and exchanges power to alleviate the congestion and avoid thermal issues. The peak-shaving logic assesses the current through an identified critical line and outputs the real power needed to avoid current magnitudes exceeding a defined threshold. The power transferred maintains a constant unity power factor.
- The voltage-control logic scenario considers the peak-shaving logic to address thermal violations however, in this case the reactive power is controlled such as to not cause any voltage issues due to the power transferred from Feeder A. The voltage-control logic operates similar to that of a capacitor bank by incrementally changing the reactive power based on the local average phase voltage magnitude. Feeder A's connection bus is monitored, and the reactive power is manipulated in increment of 100 kvar to maintain the voltage within 0.99Vp.u. and 1.02Vp.u. range.

These control logics are user-defined to demonstrate the methodology to assess the impact of a tie-point controller and more specifically in this case to address two possible issues in the studied feeders. Nevertheless, any control logics can be implemented to dictate power transfer due to any feeder specific issues and to optimize the value provided by the device in a specific scenario.

MODELLING AND SIMULATION

The yearly time-series load flow simulations were performed emulating a planning study considering CKT7 would experience a thermal constraint to be addressed in which the additional load capabilities of CKT5 could be leveraged. The base-case scenario was utilized as a benchmark to compare the tie-point controller deployment under different control logics: peak-shaving and voltage-control.

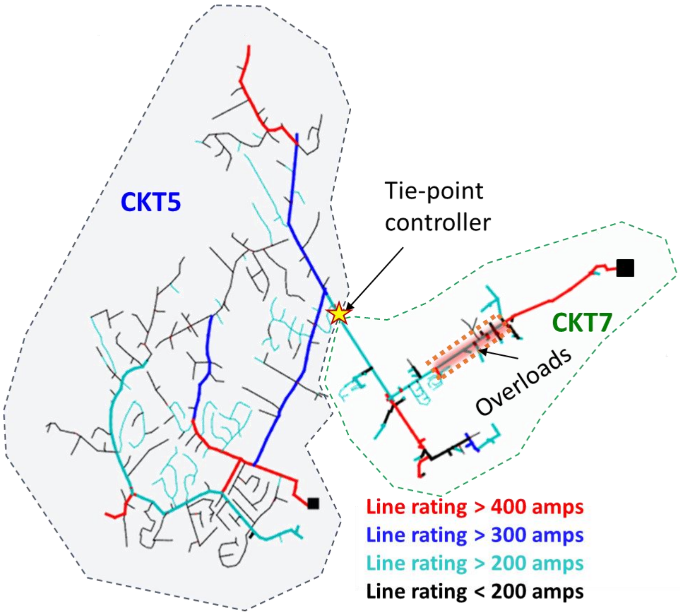

Figure 4: Circuits layout and tie-point controller location

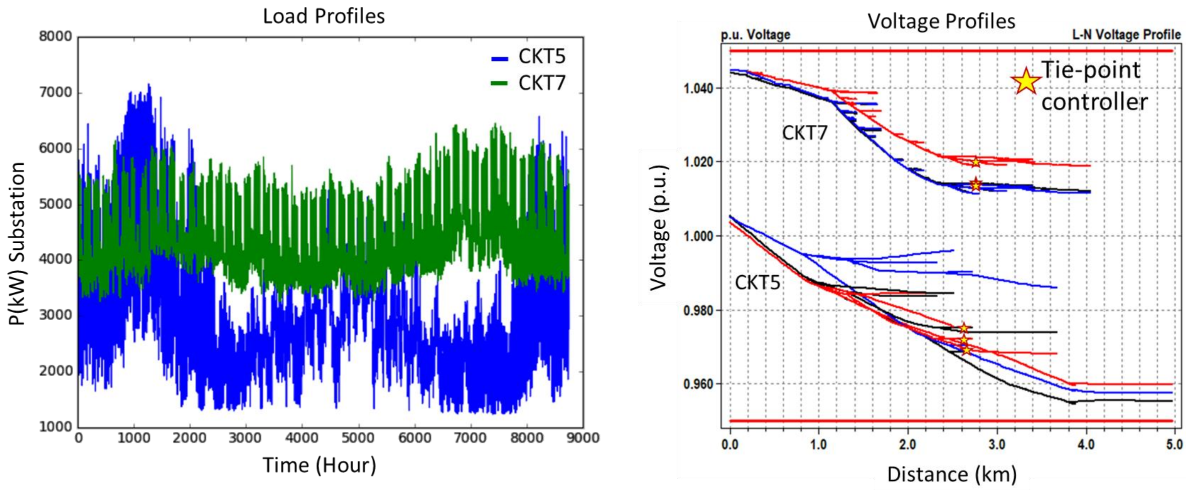

Figure 5: Circuits' characteristics a) Load shapes b) Voltage profiles

SIMULATION RESULTS

Base-Case

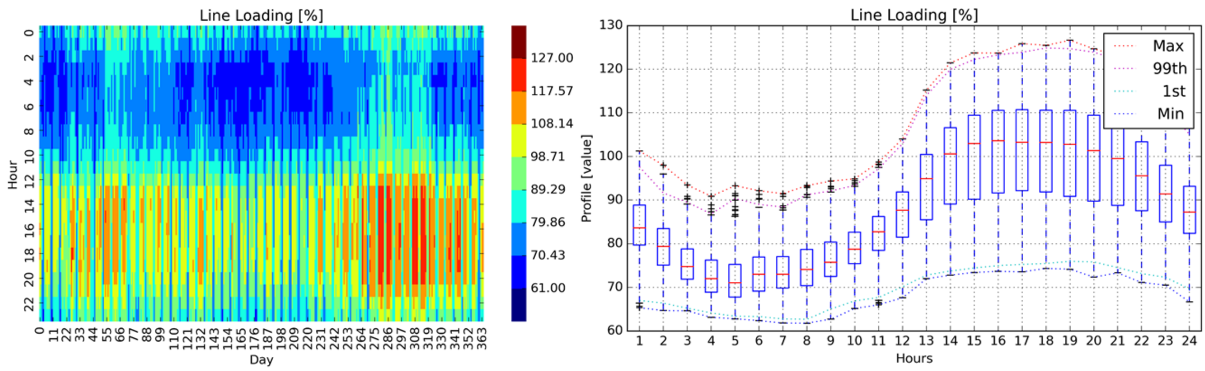

Figure 6: Base-case CKT7 monitored line loading

The selected CKT7 monitored line loading for a year can be observed in Figure 6. During a year period, approximately 1 mile of overloaded conductor would experience 2049 hours of current above its thermal rating (yellow pixels in the figure) with some instances near 130% above its limit. The heatmap provides the seasonality and daily variations of the line thermal violations. The worst violations occur between days 275 to 350; however, it's mostly uniform due to the industrial load behavior. The boxplot demonstrates that the overloads occur between 12pm-11pm. The tie-point controller can be deployed to transfer power from CKT5 to CKT7 directly to the loads at the end of the feeder, limiting the amount of power that would need to be transferred from the substation through the thermally limited line to the end of the feeder.

Peak-Shaving Logic

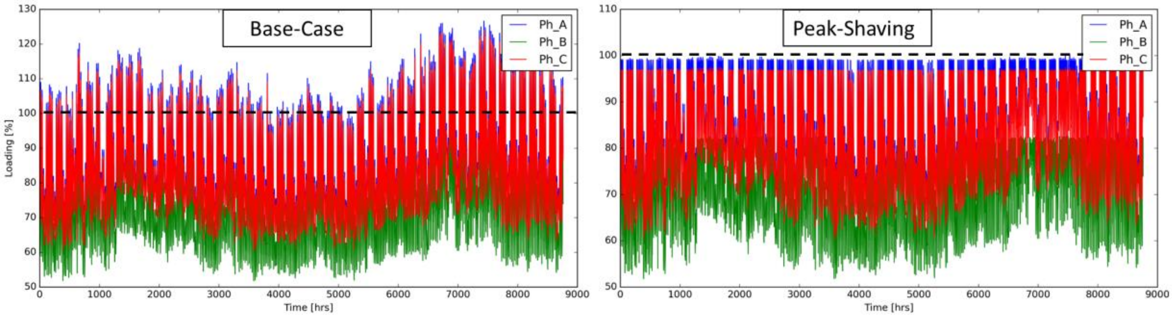

Figure 7: CKT7 monitored line loading

In this scenario, the tie-point controller transferred power from CKT5 to CKT7 based on the power transfer request by the peak-shaving logic. The overloaded line is monitored in order to prevent it from exceeding its thermal limit. Figure 7 shows line loading for each phase compared to the base-case for every time step. The line loading remained below the %-loading limit specified.

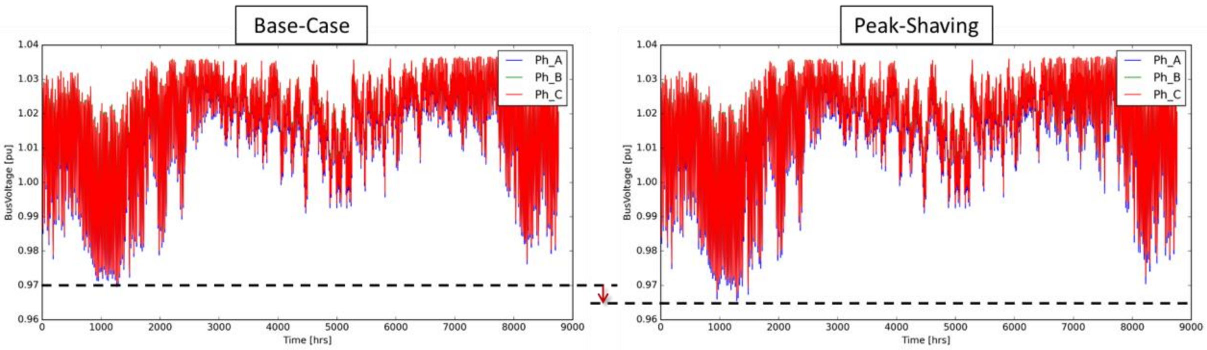

Figure 8: Peak-shaving vs base-case voltage conditions at CKT5 tie-point controller connection bus

The voltages at CKT5 tie-point controller connection bus for the full simulation period during the base-case and peak-shaving case are compared in Figure 8. While the voltage is not significantly reduced due to the power transferred, this is very dependent on a number of factors such as the location, voltage regulating equipment, magnitude of the power transferred, etc. Under different conditions the voltage drop due to the power transfer may be a cause for concern, thus the reactive power can be managed to address the voltage deviation under these circumstances.

Figure 10 displays the power transferred from CKT5 to CKT7 in order to mitigate the thermal violation, maintaining a unity power factor. The real power at each circuit are mirrors of each other since the power extracted from one feeder is injected into the other one. The heatmap of the real power transferred by the tie-point controller can be observed in Figure 11. The heatmap provides insight into the seasonal and daily operation of the tie-point controller. It directly aligns with the monitored line loading from Figure 6, with 0 kW transferred at any instance the thermal limit is not exceeded and highest power transferred for the highest % loading (between the hours of 12pm-11pm days 275 to 350). The tie-point controller losses are modelled separately as a load at the receiving end of the power transferred.

Voltage-Control Logic

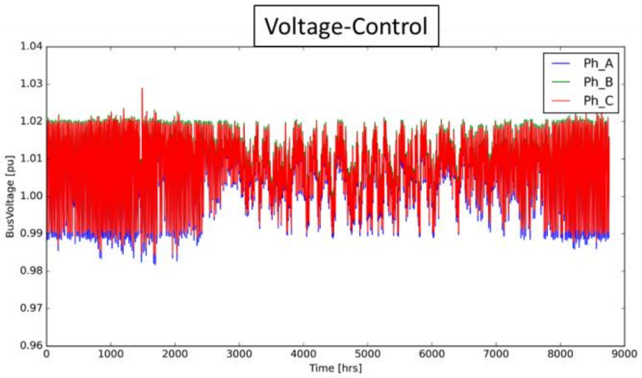

Figure 9: Peak-shaving vs voltage-control voltage conditions at CKT5 tie-point controller connection bus

In this scenario, the real power transferred from CKT5 to CKT7 remains the same thus, addressing the monitored line thermal limit violations. However, the power factor is no longer maintained at constant unity. On the contrary, the reactive power is manipulated by the voltage-control logic to maintain the average phase voltage between the 0.99Vp.u. – 1.02Vp.u. The lower bound was chosen in order to limit further voltage drop downstream of the tie-point controller. On the other hand, the upper bound was selected taking into consideration situations in which a high reactive power injection is defined in high peak conditions but may cause over-voltages in off-peak conditions. Figure 9 demonstrates the voltage at CKT5 tie-point controller connection bus for the duration of a year for the voltage-control logic. It can be observed that the voltage is predominantly maintained within the defined limits except for a couple of instances. In these instances, the reactive power requested exceeded the defined maximum threshold, 1000 kvar (Figure 10).

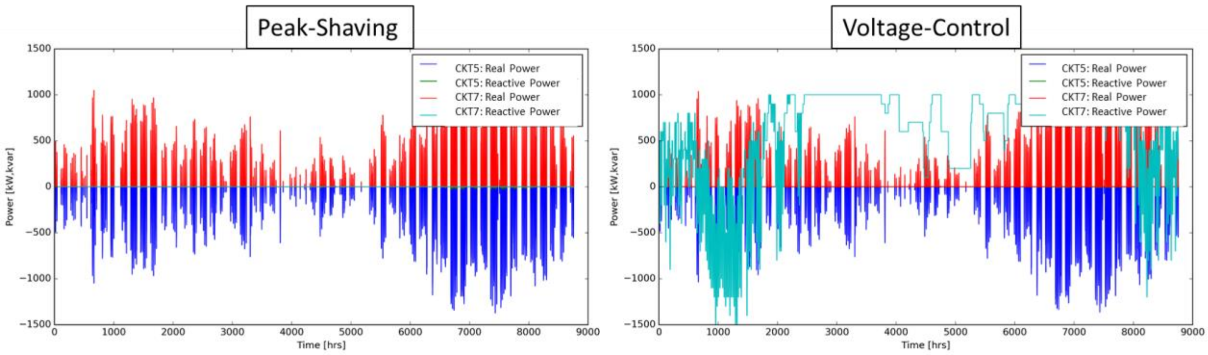

Figure 10: Peak-shaving vs voltage-control tie-point controller power transfer

The tie-point controller is not only able to address overloads and maintain the voltages (provided a user-defined control logic) but provides many other system wide benefits. Table I compares the line, transformer and voltage results between the base-case, peak-shaving and peak-shaving with voltage-control scenarios for the overall yearly simulation. In the base-case, system wide line violations consisted of over 2000 hours with 23 lines operating above their limits (above 100%

their rated capacity). However, due to the power transferred from CKT5 to CKT7 these violations were able to be avoided. Moreover, while the transformer hours of overload did not improve, the number of tap changes were significantly reduced, indicating a possible prolongation of equipment life. In the case of system wide voltages, the average voltage does not result in a significant change when the tie-point controller is implemented with either control logic. However, over-voltage violations (voltages above 1.05Vp.u.) are eliminated. In the peak-shaving scenario, the under-voltage violations are increased due to the significant power transfer. Nevertheless, under-voltage violations (voltages below 0.95Vp.u.) are significantly reduced in the case of voltage-control logic. These benefits are achieved at no significant cost to the system wide total losses (MWh, Mvarh) for the yearly simulation for all three scenarios.

Table I: System wide performance metrics

		Base-Case	Peak-Shaving	Voltage-Control
Lines	Hours Overloaded	2,049	0	0
	Total number overloaded	23	0	0
Transformers	Hours Overloaded	731	731	731
	Total number overloaded	10	10	10
	Total Tap changes	98	24	24
Voltages	Average voltage	1.021	1.021	1.017
	Over voltage violations	26,120	0	0
	Under voltage violations	20,952	27,802	3,149
Losses	Total P Losses (MWh)	2,624	2,619	2,670
	Total Q Losses (Mvarh)	6,295	6,426	6,657

DISCUSSION

The impact of the power transferred from one circuit to the other can only be observed in segments in direct path from the substation to the tie-point. Any laterals to that power flow path are not impacted by enabling power transfer at the tie point. Therefore, the tie-point controller is only able to alleviate thermally constrained lines in the direct path of power transfer. In other words, the tie-point should be downstream of the thermal constraint in the system. The magnitude of the impact that a tie-point controller has on thermal loading of a line will be proportional to the power transferred between feeders.

Unlike thermal constraints, a tie-point controller will impact the voltage not only upstream but also on downstream busses as well as nearby laterals branches of the tie point. The magnitude of the impact will vary based on the reactive power injected (or extracted) onto the feeder but the voltage difference will depend on other feeder characteristics (e.g. distance from the substation). Further system-wide benefits are possible with more sophisticated control logics and by coordinating a tie-point controller with other voltage regulating devices on the system. This is outside the scope of this study.

Another opportunity for increased operational flexibility in distribution systems is to address the different temporal behavior in the demand that distribution feeders could have, which is based on their customer diversity. For instance, the use-case used in this study modelled a feeder with predominantly industrial / commercial loads and another feeder with predominantly residential loads (see Figure 5-a). Each feeder could experience high demand at different time of the day or different days of the year where enabling power transfer could alleviate undesirable feeder conditions.

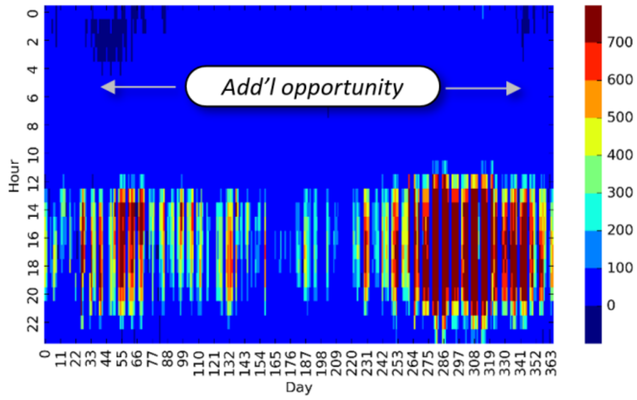

Figure 11. Heatmap of the real power transfer by the tie-point controller from Figure 10.

Similarly, electrification technologies (e.g. electric vehicles, heat pumps, PV systems, etc.) could create new dynamics in the demand with very specific temporal behavior that could impact feeders differently depending on the adoption levels. For instance, PV systems will only generate power during daytime hours and electric vehicles could potentially shift their charging schedule to different times of the day when electricity prices are lower. In the use-case in this paper, the tie-point controller operation daily and seasonal variation throughout the yearlong simulation can be visualized with a heatmap (Figure 11). In this scenario, the tie-point controller operated mostly during the afternoon and evening hours while remaining idle during the morning hours. This leaves additional opportunity for the device to transfer power not only to address thermal issues but also share available capacity across multiple feeders to accommodate additional resources on distribution network. It is also important to note that a tie-point controller could transfer power multi-directionally depending on the specific need of each feeder.

CONCLUSION

Tie-point controllers can provide controllability to the ever-evolving distribution system. Although it can address thermal and voltage violations due to the distribution system's normal operating conditions, or DER and EV interconnection, or load growth, the benefits are fully dependent on the specific feeder conditions, location, and the control logic implemented that manages the power transfer. Since these are power-electronic based devices, the real and reactive powers are able to be controlled separately providing the capability to address thermal constraints while regulating the voltage.

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