Effects of dynamic power electronic load models on power systems analysis using ZIP-E loads

Final Project Report

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Power Systems Engineering Research Center
Empowering Minds to Engineer
the Future Electric Energy System

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Executive Summary

Power grids are seeing more devices connected at the load level in the form of power electronics: e.g., data centers, electric vehicle chargers, and battery storage facilities. Therefore it is necessary to perform power system analysis with load models that capture these loads' behavior, which has historically not been done. Instead, static ZIP loads, which have constant impedance, constant current, and constant power components, have for the most part been the industry standard for load modeling analysis of power systems.

It has been posited in the research community that these new power electronic loads should be modeled as constant power loads, as the converter acts as a firewall between the network and the load. While we think that this is a suitable modeling choice for slower time scales, we think that this is a very strict modeling requirement during transient events for time domain simulations: it is hard to control voltage and current quickly enough to ensure that constant real power is delivered to the load for all time. Furthermore, constant power load models are well known to induce unstable operating conditions.

To this end, we propose ZIP-E loads, a composite load model that has a ZIP load with a dynamic power electronic, or E, load model. We model the E load as a grid following converter that consumes, instead of delivers, real and reactive power.

We believe that ZIP-E loads provide a flexible alternative for load modeling during fast time scales: ZIP-E loads adopt i.) the common industry practice of ZIP loads, ii.) the notion that power electronic loads will behave as constant power loads in steady state, iii.) an energy buffer so the constant power constraint of the load is relaxed during transient events, and iv.) a physical representation of power electronic loads capturing the dynamics of new loads being incorporated into the grid.

For now, we do not incorporate motors as loads for two primary reasons: i.) we seek to identify the modeling impact of changing constant power, or P loads, to E loads, and ii.) most modern motor loads are interfaced with variable frequency drives, which inherently have a power electronics interface of the form we choose to model here.

In addition, by modeling loads in this way, we consider fast dynamics on both generation and load, meaning that fast line dynamics could be relevant. We investigate their effect as well.

Therefore, this research is guided by the following questions:

1. What, if any, qualitative differences are there between the conclusions of small signal stability analyses of power systems that use ZIP versus ZIP-E load models?
2. Can ZIP-E loads influence inverter current dynamics in ways not otherwise manifested by ZIP models?

To address these questions, we perform studies with load comparisons: we compare ZIP to ZI-E loads (a ZIP-E load with no constant power portion) to assess the effect of modeling real life power electronic loads as constant power loads versus E loads.

Loads overall have a total real power consumption of P_0, which is split among each of the ZIP-E components. For the analysis of ZIP to ZI-E loads, we increase the P (for ZIP) and E (for ZI-E) percentage of the load in 0.1 point increments from 0 to 1, while keeping the Z to I ratio constant.

We perform small signal and transient analysis of the IEEE WSCC 9 Bus test case with ZIP and ZIP-E load models, using both static and dynamic pi line models, while changing the loading of the network. That is, the default network has a nominal operating condition for the nominal load. We take this value and scale it by a factor *load scale* in order to change the operating condition of the network, resulting in a more heavily or more lightly loaded system.

Therefore, given an operating condition of the system by *load scale*, we run a small signal and transient analysis of that operating condition for each load and line model.

For the small signal analysis, we conclude that ZIP loads destabilize networks significantly faster than corresponding ZIP-E loads. We found that at higher loading conditions, the choice of load model had a larger effect on the overall placement of eigenvalues: eigenvalues moved more as a function of load model at higher loading conditions. For the transient stability analysis, results showed significantly larger oscillations for ZIP loads relative to ZI-E loads. Further, we find that a higher network loading condition is correlated with a higher sensitivity to load model choice.

In general, these results suggest that the constant power portion of the ZIP load has a large destabilizing effect and can generally overestimate instability, and that attention should be drawn to load model choice if operating near a stability boundary.

To summarize, our contributions are:

1. An analysis on load model effects on small-signal and transient stability of the IEEE WSCC 9 Bus Test Case.
2. A series of recommendations for load models for static and dynamic power system simulation studies.
3. ZIP loads with larger constant power portions induce larger oscillations in transient simulations relative to ZI-E loads which are significantly more dampened and converge more regularly.
4. ZIPE_loads. jl - A software package for modeling ZIP-E loads compatible with PowerSimulationsDynamics.jl, a Julia-based open source simulation software for small signal, phasor, and EMT analysis of power systems.
5. An analysis of dq-abc signal relationships.

Future work includes:

1. Further studies with a larger test case.
2. Decreasing grid strength to study subsynchronous oscillations.
3. Changing generation location and portfolio to study its impact on small signal and transient analysis.

Project Publications:

[1] Gabriel E. Colón Reyes, Reid Dye, Claire Tomlin, Duncan Callaway, “Effects of dynamic power electronic load models on power systems analysis using ZIP-E loads,” *accepted to North American Power Symposium,* October 2024.

Student Theses:

[1] Gabriel E. Colón Reyes. High-fidelity modeling for modern power systems analysis and stability. PhD candidate at UC Berkeley. Expected graduation date May 2025.

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1. Introduction

1.1 Background

This work aims to study the impact of load modeling in power grids with high penetrations of power electronics converters. Among power systems components, loads have not seen many widely adopted models for transmission system simulation compared to generators, and transmission lines [1]-[5]. This can be attributed to several reasons, one of which is the inherent challenge of modeling loads: power consumption is a function of many conditions, including weather, time of day, geographic location, and even human behavior. In addition, the load from a Transmission System Operator point of view is in reality a distribution system which encompasses a lot of different components. Therefore, most of the analysis done for power system stability has been using a select few model options

Data centers, electric vehicle superchargers, large-scale battery storage, and variable frequency drives (VFDs) are examples of power electronic loads connecting on the grid, and available load models do not accurately capture their dynamics for all time scales. Moreover, any analysis is limited in scope to the results produced from the choices of models. Therefore, there exists a need for power systems analysis with models that represent loads being connected on the grid.

A survey on power system industry members in 1988 [6] found that the most common load modeling practice was constant current loads for active power loads and constant impedance loads for reactive power loads. ZIP loads, static linear combinations of constant impedance, constant current, and constant power loads, were also common, and only a small number of industry members used dynamic load models.

Another survey in 2013 [7] found that there was no industry standard for load models and that this choice varied significantly by continent. Variations of static ZIP loads, however, were the most common model, constituting 70 % of industry load models worldwide. Another common practice in the study was converting a ZIP load into an equivalent exponential model with a non-integer exponent. The survey also found that it is a common practice in the United States of America to use a composite load model incorporating both a static load component in the form of a ZIP load and a dynamic load component (typically an induction motor) in parallel.

Other load models have been proposed to capture a load's dependence on frequency. These usually take the form of a linear combination of two ZIP load models [6]. A similar attempt is made by the EPRI LOADSYN and ETMSP static load models [6]. These, however, according to the surveys, were not widely adopted by industry members.

Despite the 25 year gap between the surveys, the most recent does not show significant changes in the way industry models loads despite the increasing level of power electronics loads on the grid. This further means that corresponding analyses have not had accurate representations for power electronic loads.

In 2022, the IEEE Standards Association and IEEE Power and Energy Society published a guide for load modeling for simulations of power systems [8]. The guide acknowledges that only a few load models are widely accepted among industry members. It also references more recent work that has modeled power electronic devices as loads, but these are constrained to parameter fitting of the standard static ZIP load. For dynamic loads, motors are the most common model [9], and the exponential recovery load model captures aggregate transmission-level load dynamics [10].

Lastly, the state-of-the-art load model for phasor domain simulations is the WECC composite load model [11] but is limited to static models for power electronic loads, except for VFDs [12]. It, however, does not represent inverter control loops relevant for higher frequency dynamics. A recent paper [13] uses dynamic power electronic load models for EMT studies with line dynamics but assumes no load heterogeneity.

In sum, loads are typically modeled as static ZIP loads, with motors seldom incorporated for dynamic simulations. Further, there is no well-motivated way of choosing how a load is modeled for different kinds of studies. This suggests for the last 40+ years industry has largely been using the same models for all analysis.

It has been posited that power electronic loads need to be modeled as constant power loads for analysis [8], however, this static model choice is an approximation of a dynamic device. Therefore, while this may be an accurate modeling choice for slow time scales, we believe we should model power electronics load with corresponding dynamics for analysis on fast time scales. This is further motivated by concerns regarding current saturation limits for inverters [14] and how this affects stability conclusions and inverter current dynamics. So, there is a gap in the literature for analysis of power systems with models that represent the new devices being connected.

Therefore, in this work we propose ZIP-E loads, a composite load model including a static ZIP model, and a power electronic load, which we denote as an E load, for the analysis of power systems with power electronic loads. We model this load as a grid-following inverter that consumes instead of delivers power: it is a rectifier, as are the power electronic loads described. An E load is meant to capture the dynamics of those power electronic devices, and the ZIP-E load is meant to capture heterogeneity in the load profile.

For now, we do not incorporate motors as loads for two primary reasons: i.) we seek to identify the modeling impact of changing P loads to E loads, and ii.) most modern motor loads are interfaced with VFDs, which inherently have a power electronics interface of the form we choose to model here.

To our knowledge, this is the first small signal and transient study of power systems with heterogeneous load models that includes physics-based models for power electronic loads.

We believe that ZIP-E loads provide a flexible alternative for load modeling during fast time scales: ZIP-E loads adopt i.) the common industry practice of ZIP loads, ii.) the notion that power electronic loads will behave as constant power loads in steady state, iii.) an energy buffer so the constant power constraint of the load is relaxed during transient events, and iv.) a physical representation of power electronic loads capturing the dynamics of new loads being incorporated into the grid.

Further, by modeling loads in this way we consider fast dynamics on both generation and load, meaning that fast line dynamics could be relevant. We investigate their effect as well.

This research is guided by the following questions:

- What, if any, qualitative differences are there between the conclusions of small signal stability analyses of power systems that use ZIP versus ZIP-E load models?
- Can ZIP-E loads influence inverter current dynamics in ways not otherwise manifested by ZIP models?

Another direction of this project has been in understanding relationships between abc and dq signals.

Power systems are generally modeled with respect to a static abc reference frame. They can also be modeled relative to another static reference frame, the αβ0 frame, and the rotating dq0 reference frame. Modeling with respect to these reference frames is done by taking a quantity called the space phasor, and then projecting it onto the abc, αβ0, and dq0 frames. This can be done also by using mathematical transformations to convert the signals from one reference frame to another.

In the case of balanced three phase abc signals, the 0 component of the αβ0, and dq0 representations is always equal to zero so it can be dropped and we end up with an αβ and dq system.

A three phase abc signal is characterized by each phase's amplitude, frequency, and phase. In the case of a *balanced* three phase abc signal, it needs only to be characterized by an amplitude and phase because the phase shifts are predefined to be $2\pi/3$ between each pair of phases, and the frequency is assumed constant. This means that having three signals is redundant because there are only two degrees of freedom and thus all the information can be captured by two signals in the static αβ. Note that because the abc and αβ reference frames are static frames, a space phasor that is projected onto both frames will produce signals of the same frequencies.

A dq system representation is useful for power system analysis for many reasons. One of those is that signals that oscillate in the abc frame state space and form limit cycles converge to points in the dq state space. Therefore, eigenvalue analysis is more straightforward in the dq frame because it is not obvious how to linearize about an operating point in the abc frame since signals generally oscillate, and even if we do linearize it is not clear what meaning eigenvalues will have since the linearization will be valid around a single operating point, and not the oscillatory trajectories of the signals.

Transmission system operators are generally interested in oscillations relative to the abc frame. For example, subsynchronous oscillations are an important topic of interest. However, if we perform an analysis in dq it is not immediately obvious how oscillations on this reference frame translate to oscillations in the abc frame. We aim to address this in this note by taking a signals-based approach.

This work's contributions are:

- An analysis of load model effects on small-signal and transient stability of the IEEE WSCC 9 Bus Test Case.
- A series of recommendations for load models for static and dynamic power system simulation studies.
- ZIP loads with larger constant power portions induce larger oscillations in transient simulations relative to ZI-E loads which are significantly more dampened and converge more regularly.
- An analysis of relationships between abc-dq signals

1.2 Report Organization

The remainder of the paper is organized as follows. Section 2 presents the load models we use, and Section 3 the corresponding load portfolios. Section 4 discusses the test case we experiment with, Section 5 shows results and discusses analysis, and Section 6 includes the derivation between abc and dq signals, and Section 7 concludes the report.

2. Power systems loads

We define a load at the transmission level as an aggregation of all circuits and devices downstream from the transmission circuit, including but not limited to the distribution grid, commercial loads, industrial loads, domestic loads, and devices.

Power systems loads are categorized as static or dynamic. Static refers to the power consumption at that load being defined as an algebraic relationship between power and voltage. Dynamic refers to having a differential equation model for the variables that dictate power consumption. Composite loads combine both static and dynamic load models in parallel.

An exponential load model, also called a voltage dependent load model, relates the power consumption of the load to a power of the normalized voltage. It takes the following form.

$$P_{exp} = P_0(\frac{V}{V_0})^{n_P}$$
$$Q_{exp} = Q_0(\frac{V}{V_0})^{n_Q}$$

Here, P_0, Q_0, V_0 are the nominal real power, reactive power, and voltage magnitude for the load. V is the voltage magnitude at the load. n_P and n_Q are the exponents of the model.

The exponential model is inherently a static load model because the voltage magnitude V which dictates the power consumed by the load is determined by the network, and does not vary as a function of the load behavior.

A ZIP or polynomial load is the convex combination of three exponential loads: a constant impedance load model (defined by $n_P = n_Q = 2$), a constant current load model (defined by $n_P = n_Q = 1$), and a constant power load model (defined by $n_P = n_Q = 0$). Mathematically it is defined as follows.

$$P_{ZIP} = P_0(\eta_Z(\frac{V}{V_0})^2 + \eta_I(\frac{V}{V_0})^1 + \eta_P(\frac{V}{V_0})^0)$$
$$Q_{ZIP} = Q_0(\gamma_Z(\frac{V}{V_0})^2 + \gamma_I(\frac{V}{V_0})^1 + \gamma_P(\frac{V}{V_0})^0)$$

$\eta_z, \eta_I, \eta_{P,}\gamma_z, \gamma_I, \gamma_P$ are weights for each load type. Electrically, it is equivalent to the three loads in parallel.

In this study, we model E loads as grid-following inverters with standard real and reactive power outer loop PI controls, PI inner loop current controls, an averaged inverter model, a phase-locked loop, and an LCL filter, as in [13].

Contrary to the ZIP load, an E load is a dynamic load model because the current drawn is described by a differential equation. The power consumed by an E load model is:

$$P_E = \frac{1}{2}(v_d i_q + v_q i_q)$$
$$Q_E = \frac{1}{2}(v_q i_d - v_d i_q)$$

v_q, v_d are the load bus' per unit capacitor voltage dq components. i_d, i_q are the per unit current dq components drawn by the inverter defined by a system of ordinary differential equations. A detailed model can be found in [15].

A ZIP-E load is a convex combination of a ZIP load and an E load model, and the power it consumes is as follows.

$$P_{ZIP-E} = P_0(\eta_Z(\frac{V}{V_0})^2 + \eta_I(\frac{V}{V_0})^1 + \eta_P(\frac{V}{V_0})^0 + \eta_E \frac{1}{2}(v_d i_q + v_q i_q))$$
$$Q_{ZIP-E} = Q_0(\gamma_Z(\frac{V}{V_0})^2 + \gamma_I(\frac{V}{V_0})^1 + \gamma_P(\frac{V}{V_0})^0 + \gamma_E \frac{1}{2}(v_q i_d - v_d i_q))$$

Note the addition of the $\eta_{E,}\gamma_E$ terms which capture the power consumed by the E part of the load. Moreover, it is now the case that the load consumes real and reactive power not only as a function of the voltage at the load bus, but also as a function of the current drawn by the load.

As a part of this work, we develop ZIPE_loads.jl, an open source Julia-based package to extend the modeling capabilities of PowerSimulationsDynamics.jl (PSID.jl). It leverages already available models in PSID.jl to allow the user to model ZIP-E load variations.

3. Load Composition

Based on a study of the literature, there is no standardized way to choose ZIP load coefficients based on an understanding of the load behavior. Therefore, we outline modeling options based on what industry has done, and propose alternatives.

One option is as it was done in the 1980s [6]: real power loads as static constant current loads, and reactive power loads as static constant impedance loads. Another is what was done in the 2000s: real and reactive power loads as static ZIP loads. However, it's not clear how to select coefficients [7]. Based on [7], the USA is the only country where a substantial number of industry members run simulations with composite load models. [1] proposes a few coefficient options for the last two options.

We consider a constant impedance test case as a benchmark, as this is the most common load type in research. We consider cases with P or E load contributions (through η_P and η_E, respectively) in 10 percentage point increments from 0 to 100 % with the remainder of the load constituting of equal parts Z and I, thus comparing ZIP loads to ZI-E loads by choosing η, γ as follows.

For ZIP loads:

$$\eta = \gamma = [\eta_Z \; \eta_I \; \eta_P \; \eta_E] = \left[\frac{1-x}{2} \; \frac{1-x}{2} \; x \; 0\right]$$

For ZI-E loads:

$$\eta = \gamma = [\eta_Z \; \eta_I \; \eta_P \; \eta_E] = \left[\frac{1-x}{2} \; \frac{1-x}{2} \; 0 \; x\right]$$

where

$$x \in \{0.1, 0.2, \ldots, 1.0\}$$

Note that for each x we have a particular load portfolio. Constant power and full E loads are defined by $x = 1.0$. This comparison will allow us to test differences of the effects modeling power electronic loads as P loads or E loads.

4. Test Case

In this work, we use a modified version of the IEEE WSCC 9 Bus test case shown in Fig. 1. It is composed of a synchronous machine (SM), a grid-forming converter (GFM) operating as a virtual-synchronous machine (VSM), and a grid following inverter (GFL) as sources. It has three loads, and six transmission lines. For lines, we use algebraic and dynamic pi line models, *statpi* and *dynpi* respectively. Models and data for these devices are according to [5], [16]. We stay consistent in our choice of models for purposes of comparing results across papers.

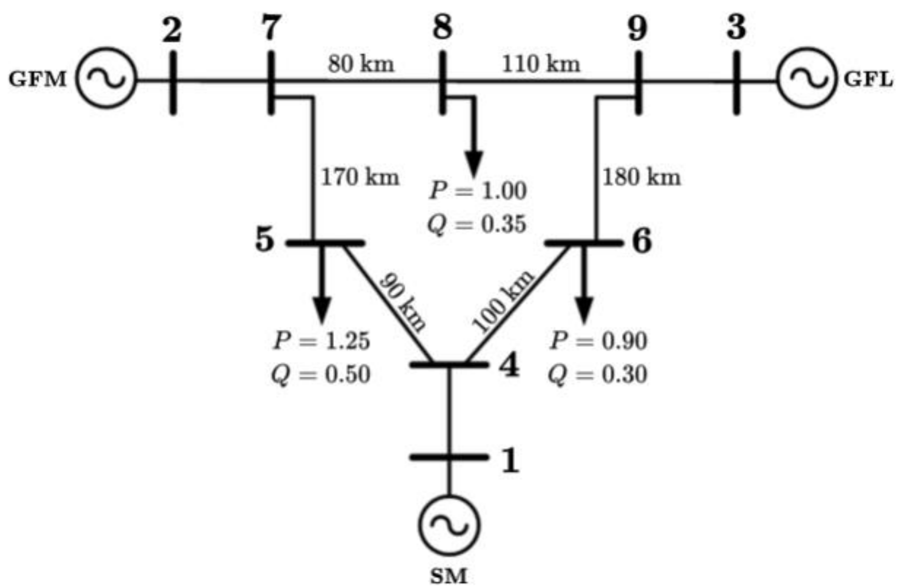

Fig. 1: Modified IEEE 9 bus test system. SM at bus 1 (reference bus), VSM GFM at bus 2, GFL at bus 3. Note that we do not use a slack bus for our simulations.

4.1 Experiments

The network's nominal operating condition is found by solving a power flow, and then loads are scaled by a constant factor we denote *load scale*. We then scale all generator power set points in proportion to *load scale*. For each load model, for each line model, and for each *load scale* value, we run a small signal and transient analysis.

For the small signal studies, given a single *load scale* value (or, equivalently, a network loading condition), all line and load models will produce the same power flow solution. We verify the stability of this operating condition to address our guiding questions.

For the transient analysis, we trip the heaviest loaded branch as given by the power flow solution, which is the line connecting buses 4 and 5 in this case. We choose to measure the current flowing into the network at Bus 3 as a proxy variable for inverters since it could be saturated if control limits are reached. We evaluate time domain simulations to see current behavior differences to address our guiding questions.

5. Simulation result and analysis

Code and results are publicly available in our GitHub repository: https://github.com/gecolonr/loads for reproduction, which includes a set of interactive plots for the reader to further explore our results if interested.

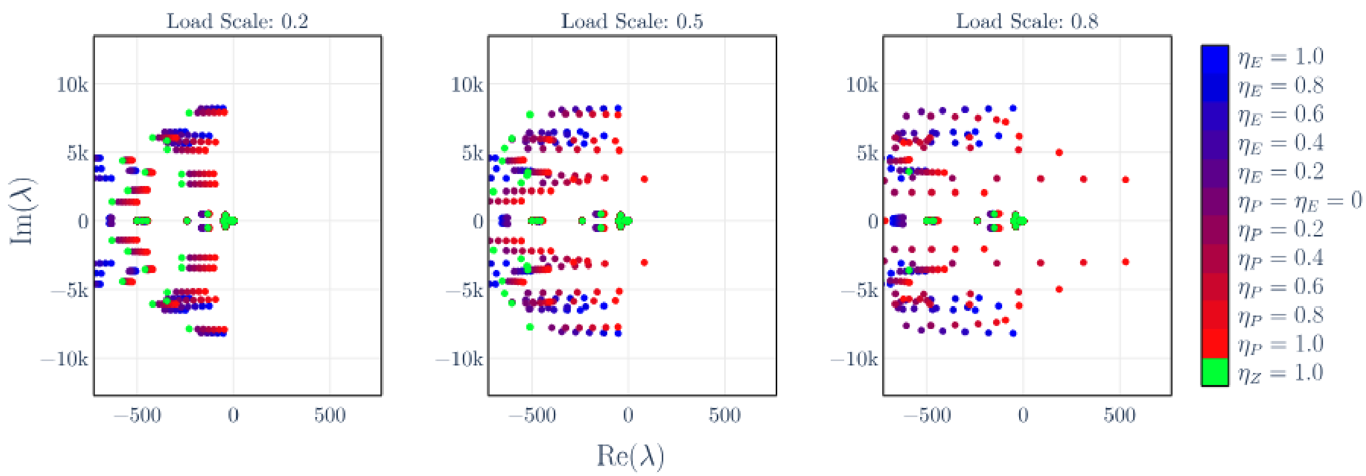

Fig. 2: Network eigenvalues with *dynpi* line model at *load scales* of 0.2, 0.5, and 0.8 increasing to the right.

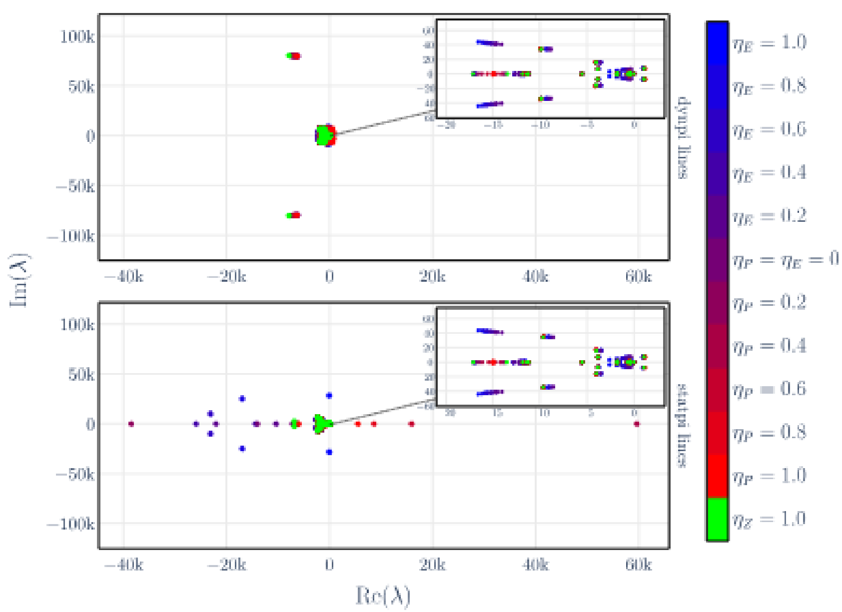

Fig. 3: Eigenvalues at load scale=1.0 for *dynpi* (top) and *statpi* (bottom) line models. ZI-E loads are in blue and ZIP loads are red in 10 % increments as given by the heatmap bar on the right.

5.1 Small Signal Analysis

We study the eigenvalues of the network under different conditions.

5.1.1 Load model effect

When comparing eigenvalues of ZI-E loads with high E values to ZI-E loads with low E values, there was no consistent trend. Some shifted to the right, others to the left, this is likely dependent on the influence of particular states on those eigenvalues. This is also true for ZIP loads. This can be appreciated in Fig. 2.

Results further showed that at low network loading levels, load model variations had limited effect on eigenvalues and thus on stability conclusions. This can be seen in the leftmost plot in Fig. 2, with all load models concluding in a stable operating condition. This suggests that when the network has enough buffer between the operating condition and the instability boundary, the choice of load model has a small impact on system behavior and stability conclusions.

As we increase the network loading, however, we find that ZIP load cases move the eigenvalues to the right more quickly than ZI-E loads. Several cases showed a stable operating conclusion with ZI-E loads, but an unstable conclusion with ZIP loads. The center plot in Fig. 2 shows an example.

As the network loading further increased, we found that the eigenvalues for ZIP load cases were very far right on the complex plane, whereas eigenvalues for ZI-E cases were unstable but very close to the $j\omega$ axis with real parts less than 1. This suggests that, despite being an unstable operating condition, it is much more stable relative to the common industry practice of ZIP loads. This can be appreciated on the rightmost plot of Fig. 2. Further, because these ZI-E cases are barely unstable, this operating condition might be stable with differently tuned controller gains for the generating devices.

Lastly, in addition to eigenvalues moving to the right under higher loading, the effect of load model on a particular eigenvalue is more pronounced as evidenced by more spread eigenvalue maps on Fig. 2 as loading increases.

These results support the hypothesis that a low stability margin correlates with higher sensitivity to load model choice presented in [17]. In situations where the distance to the timinstability boundary is small, modeling constant power loads with the typical algebraic model could lead to significantly overestimated instability. The E component seems to aid in remedying this.

5.1.2 Load model effect with line dynamics assumption

A consistent theme across all cases was the stabilizing effect of the *dynpi* line model, particularly at higher load scales. An example of this can be seen in Fig. 3 where eigenvalues for the *statpi* model have significantly larger real parts relative to *dynpi* model. For the *statpi* model we found several cases in which there is a singularity where an eigenvalue moves from minus infinity to positive infinity as loading is increased, suggesting a modeling limitation. This does not happen for the *dynpi* model. Further, *dynpi* lines tended to filter out many high frequency eigenvalues with the exception of complex conjugate pairs with frequency of about 12.5 kHz suggesting they could be high frequency states of the dynamic lines, these are the clusters on the top plot of Fig. 3.

All other eigenvalues had frequencies less than 1.2 kHz, whereas for the *statpi* case, many unfiltered modes had frequencies of about 4-5 kHz. Further, we had several line parameters and changing between them didn't significantly affect the placement of the least stable eigenvalues nor the dynamic behavior of the variables we considered.

5.2 Transient analysis

For the transient analysis, we measure the magnitude of the GFL inverter's filter current at Bus 3.Fig 4.

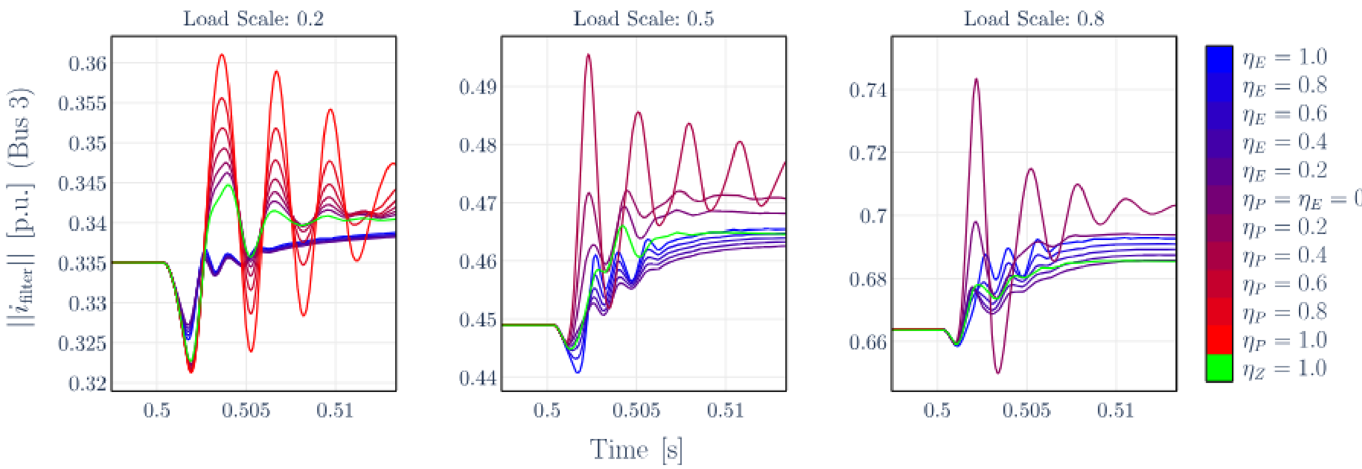

Fig. 4: Bus 3 inverter current magnitude after a branch trip on line 4-5 with *dynpi* lines.

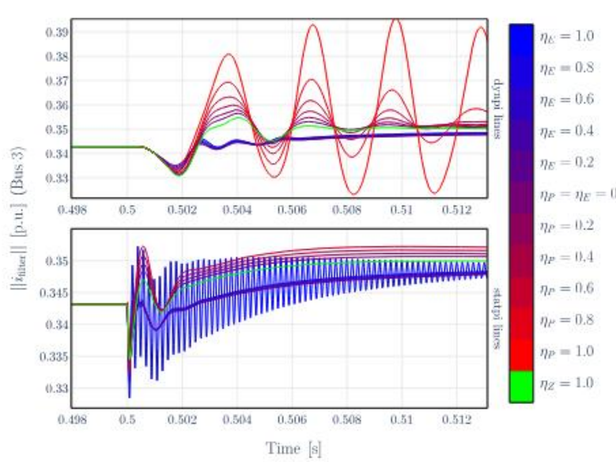

Fig. 5: Transient simulation of Bus 3 inverter current magnitude after a branch trip of line connecting Bus 4 and Bus 5. *load scale* = 0.25.

5.2.1 Load model effect

We typically saw two families of traces post disturbance: one trace family for ZIP loads and another for ZI-E loads. When they both converged, they had the same steady-state solution but different ways to reach it. Cases with ZIP loads had larger overshoots relative to cases with ZI-E loads. Further, ZIP cases with larger P percentages tended to have larger amplitude than those with lower P percentages. The same was true for ZI-E cases.

Under low loading conditions, ZIP loads cases with η_P > 0.6 or higher were generally unstable, but all ZI-E cases were stable, even with an E percent of 100 %.

This can be appreciated in the leftmost plot of Fig. 4. Further, as *load scale* increased, cases with higher ZIP were the first to destabilize, which is consistent with the small signal analysis. This is further appreciated in the center and rightmost plots in Fig. 4 where several of the high-P cases fail to converge, and those that do converge have significantly larger overshoots relative to all the ZI-E cases. This implies that E loads induced more damping relative to P loads for both low and high-frequency oscillations.

The long-term oscillations of the ZI-E loads were not ultimately problematic. In stable cases, they disappear quickly, and in unstable cases, they follow a similar trend to ZIP loads.

5.2.2 Load model effect with line dynamics assumption

High-frequency oscillations on *statpi* lines were seen for both high-E and high-P loads, but decreased rapidly with decreasing E or P percentage. Only high-E loads show these oscillations because in high P cases they grew too large and the simulations did not converge. Smaller oscillations are also visible for $\eta_E = 0.8$, but they are damped within the first millisecond. This suggests a η_E or η_P threshold for stability in this mode.

In most cases, the *dynpi* line model clearly filters to 4-5 kHz frequency modes in the system present in the *statpi* case. This is consistent with the small signal analysis, and can be appreciated in Fig. 5.

5.3 Network loading

Under this SM-GFM-GFL generation configuration, the network loading needed to be low (*load scale* = 0.2) to ensure a stable operating condition for all load and line models. We compared this to the case with SMs in all generation buses and found that for *load scale* = 1.0 the network equilibrium was stable except for ZIP loads with $\eta_P > 0.4$ with both *statpi* and *dynpi* lines. This complements the finding that ZIP loads are the most difficult loads to stabilize, and speaks to the relevance of generation configuration contributing to the stability of the equilibrium condition. Further, it implies that the loading a network can tolerate is low without inducing an unstable operating condition when there are power electronics both at the generation and load levels.

5.4 Computational burden

Networks with ZI-E loads have about 30 more dynamic states than those with ZIP loads due to the three E loads. Despite that, we found that *statpi* cases' runtime was not significantly impacted, and *dynpi* simulations with ZI-E loads ran 7-10 times faster than corresponding ZIP load cases, suggesting that ZIP loads can be more computationally intensive than corresponding ZI-E loads.

6. abc-dq signals

We now shift our attention to drawing precise relationships between abc and dq signals. This is motivated by the fact that power systems analyses are often conducted in the dq rotating reference frame. However, if we want to study subsynchronous oscillations in variables in the abc frame, for example, it is not clear from the literature how signals in dq are uniquely related to signals in abc and vice versa. In this work, we address this task.

6.1 abc to dq

Consider a three phase balanced abc signal of the following form

$$x_a(t) = \hat{x}\, cos(\omega t + \theta_0)$$
$$x_b(t) = \hat{x}\, cos(\omega t + \theta_0 - 2\pi/3)$$
$$x_c(t) = \hat{x}\, cos(\omega t + \theta_0 - 4\pi/3)$$

where $\hat{x}$ is the amplitude and ω , θ_0 are the frequency and phase offset.

We can take a series of arbitrarily many three phase balanced abc signals of this form and project them onto the dq rotating frame through the use of the space vector. In such a case, we arrive at

$$x_d = \sum_{i=1}^{N} \hat{x}_i cos((\omega_i - \omega_0)t + \theta_i)$$
$$x_q = \sum_{i=1}^{N} \hat{x}_i sin((\omega_i - \omega_0)t + \theta_i)$$

where $\hat{x}_i$ are the amplitudes of the individual sinusoidal functions ω_i, θ_i are the frequencies and angle displacements of each three phase balanced abc signals, and ω_0 is the frequency of the rotating dq frame.

From inspection, a few observations can be made.

- The amplitude and frequency of the i'th dq components are identical.
- The amplitudes in dq are preserved from abc.
- There is a natural phase offset between the d and q components because of the cosine in d and sine in q. More specifically, for abc frequencies $f_i \geq f_0$, the q component lags the d component by π/2. Otherwise, the q component lags the d component by 3π/2
- For a three phase balanced signal of frequency f_i in abc coordinates, it will project onto dq as signals of frequency $|f_i - f_0|$. Note that this means that frequencies $f_i < 2f_0$ will project as frequencies less than f_0 in dq.

6.2 dq to abc

Now let's consider a dq signal with same frequency and amplitude in the dq components along with a DC term but different phase offsets, as follows.

$$x_d + j\,x_q = \alpha_0 + \alpha_1 cos(\xi_1 t + \phi_1) + j(\alpha_0 + \alpha_1 cos(\xi_1 t + \rho_1))$$

This quantity can be projected onto the abc frame and it can be shown that if

$$\rho_1 = \phi_1 - 3\pi/2$$

then if the frequency of the dq signal is less than the frequency of the rotating frame, this signal will project onto abc only as a subsynchronous signal.

On the other hand, if

$$\rho_1 = \phi_1 - \pi/2$$

the dq signals will project onto abc as supersynchronous signals exclusively. However, if neither of these conditions are met, then they will project as both sub and super synchronous signals in abc. This result can be extrapolated to arbitrarily many signals in d or q components. That is, if this specific condition doesn't hold, then the resulting abc signals will be both sub and supersynchronous.

From further inspection, it can be seen that:

- The amplitude of the dq signals is preserved by abc signals
- Dq signals will in general project onto abc as both sub and supersynchronous signals in abc
- In the specific scenario where the q component lags the d component by $\pi/2$ or $3\pi/2$ then dq signals will appear in abc only as super synchronous or subsynchronous uniquely.

7. Conclusions

In this work we perform small signal and transient stability analysis for power systems using a new composite load model, ZIP-E loads, for more realistic power electronics load modeling of power systems at the transmission level. We further develop ZIPE_loads.jl, an open-source load modeling package to model these loads in PSID.jl. We perform experiments on the IEEE WSCC 9 Bus test case to test how changing line and load models affect stability.

In the context of our guiding questions, we found that: i.) The choice of load model matters less when the network is lightly loaded, which corresponds to when the operating condition is far from its stability boundary. As the system is more heavily loaded and approaches the stability boundary, eigenvalue placement changes more drastically in relation to the load model, and ZIP loads result in an unstable operating condition significantly earlier than corresponding ZI-E loads. ii.) ZI-E loads showed a different family of traces relative to ZIP loads: they showed more damping, significantly smaller overshoots, and convergence to the slow modes much quicker. While overall trajectories of ZI-E loads are different than ZIP loads, they have the same steady state behavior in cases where both converge, as expected.

We conclude that in general load models are important for both small signal and transient analysis for power system, especially under stressed conditions. Approximating power electronics loads behavior as ZIP loads could result in unrealistic unstable conclusions far more quickly than could actually happen. The conclusions drawn from cases with ZI-E loads can be significantly different from those with ZIP loads both for small signal and transient analysis. Because of the large amounts of power electronic loads getting connected on the network, we believe ZIP-E loads make a promising attempt and capturing their dynamics so that we can arrive at reliable and trustworthy results.

This work results in the following recommendations: i.) if a particular system is operating at a condition far from a stability boundary, and that is known prior to running a simulation, pick the least expensive computational load or easily to interpret model, a constant impedance model would be suitable, ii.) if the network is close to a stability boundary, constant power loads will overestimate instability, therefore, use ZI-E load models, iii.) between *statpi* and *dynpi* line models, use *dynpi* for both transient and small signal analysis.

Further, our theoretical analysis between signals in abc and dq reference frame results in a clear relationship between these signals in order to uniquely conclude whether oscillations or subsynchronous, supersynchronous, or both when using any reference frame for analysis.

Future work includes changing the location of the generators, the generation portfolio, and varying the system's grid strength to explore low-frequency oscillations.

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