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### Development and Implementation of Composite Load Model in WECC

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### SUMMARY

This paper provides an overview of a multi-year effort to develop and implement a composite load model for power system planning and operational studies by the utilities in the Western US Interconnection. The composite load model is a significant improvement over conventional static load model, as it better captures both damping of inter-area oscillation damping as well as events of Fault-Induced Delayed Voltage Recovery. The paper describes the structure of the composite load model, and the processes for creating and managing load model data sets for various climate zones and seasons in the Western Interconnection. The paper describes utility efforts to validate model using system disturbance recordings.

### KEYWORDS

Power system modeling, load modeling, end-use testing, load composition, disturbance monitoring

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Western Interconnection has made significant advancements in dynamic load modeling in the past 10 years. A composite load model was developed, tested and implemented in all major production-level grid simulators, including General Electric's PSLF, PowerWorld Simulator, and Siemens PTI PSS®E. Load composition data sets are developed for 12 climate zones across the West, as well as for several types of industrial loads. Load composition data is developed for 24 hours, four seasons, and various types of substations (residential, commercial, mixed and rural). Tools for load model data management have been developed, and processes for creating load model records are put in place. Model validation and system impact studies have been performed, and phased implementation is approved.

## I. HISTORY OF LOAD MODELING IN WECC

Accurate power system models are required for reliable and economic power system operations. Models are used to predict the power system response to contingencies under current system conditions, as in real-time operating environment, and under future expected system conditions, as in expansion and operational planning horizons. Ultimately, the system studies are used for making capital investments in power system and setting system operating limits. Accurate models are now required by several NERC Reliability Standards.

Load representation historically has been the least accurate component of the power system model, in part due to its complexity and it part due to limitations of the computing technology of the time. Historically, load models were represented with static characteristics in the interconnection-wide power system studies, mainly constant current for active power and constant impedance for reactive power. Motor models were used only in special studies, such as stability studies for industrial sites, or reproduction of system events.

The EPRI Loadsyn project in 1990s led to the development of static ZIP models, where components are represented as a combination of constant impedance ("Z"), constant current ("I") and constant power ("P") components [4]. Several utilities adopted static ZIP representation, a few utilities performed system tests to quantify ZIP coefficients. IEEE attempts to introduce dynamic load modelling in 1990's [4] did not get much traction in the industry. The vast majority of the industry continued using constant current active power representation.

Western Electricity Coordinating Council (WECC) adopted a dynamic load model for planning and operating studies in early 2002, where 20% of load was represented with induction motors for all seasons [8]. The model was "interim" to address immediate operational issues of the California-Oregon Intertie following model validation of July 2 and August 10 1996 outages, and August 4 2000 oscillation event. The dynamic motor component was necessary to more accurately capture inter-area oscillation damping.

Events of Fault-Induced Delayed Voltage Recovery (FIDVR) were recorded first in Southern California, Florida, and Atlanta Metro area in 1980's and 90's. Southern California Edison (SCE), Florida Power and Light (FPL), and Southern Company developed detailed dynamic models for their regions to study the system impact of residential air-conditioner stalling. The models included a distribution equivalent and required special models for residential air-conditioners [5-7]. The models were used for special studies, not on interconnection-wide basis.

Model validation studies that followed July 2 and August 10 1996 Western Interconnection system outages argued the need for dynamic load modeling to better capture inter-area oscillation damping. The recommendation was echoed by the studies of a system even on August 4 2000, when marginally damped inter-area power oscillations were observed in the West. Furthermore, the increased number of the FIDVR events in Southern California and Desert Southwest made dynamic load modeling a high priority for WECC.

## II. COMPOSITE LOAD MODEL DEVELOPMENT

WECC formed a Load Modeling Task Force (LMTF) in 2002 tasked to develop a composite load model for interconnection-wide planning and operating studies to provide a more accurate representation of load response to power grid disturbances. The model structure used by SCE and FPL

was used a starting point for the composite load model development. WECC prototyped successfully the composite load model interconnection-wide in 2005 using explicit representation. General Electric implemented the first version of the model in its PSLF simulator in 2007. Figure 1 shows structure of WECC composite load model. The main features of the model are (a) recognition of electrical distance between a transmission bus and where end-uses are connected, and (b) representation of diversity of electrical end-uses.

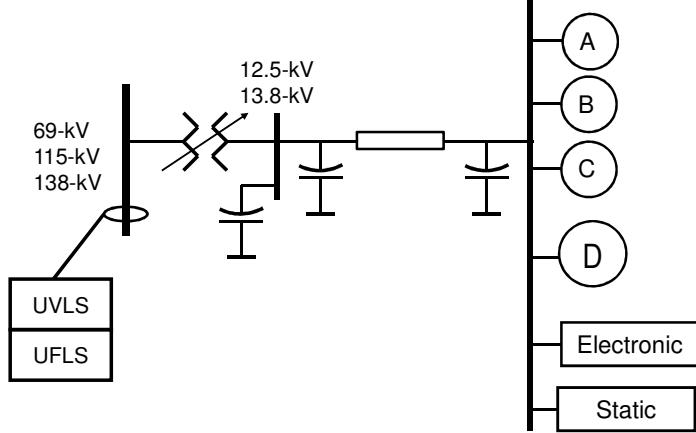


Figure 1: WECC composite load model

It was recognized that single-phase compressor motors, used in residential air-conditioners and largely responsible for FIDVR events, cannot be represented with three-phase motor models and require special modeling. SCE, BPA and EPRI conducted extensive testing of residential air-conditioners to determine their dynamic response characteristics to voltage and frequency disturbances [3]. WECC developed a performance model to represent the system impact of single-phase air-conditioners in positive sequence simulations. Model parameters were derived based on the initial equipment tests [3]. However, based on model validation and system impact studies, as well as additional test data from BPA and disturbance recordings from SCE, WECC concluded that the developed model provides more conservative results compared to actual experience. While the model [3] represents well the system impact of the air-conditioner stalling, more work is needed to be able to predict whether and how many of air-conditioners stall during a fault. Recognizing that the efforts to improve the air-conditioner modelling need to continue, WECC adopted a phased approach for implementing the composite load model. Phase 1 assumes that compressor motors ride through a fault and do not stall. Phase 2 will be implemented when the single-phase motor model is sufficiently validated against actual system events, and appropriate requirements are developed for transient voltage dip and recovery.

#### A) Distribution Feeder Equivalent

Distribution systems are very complex, and it is impractical to model their detail in the interconnection-wide transient stability studies. The composite load model is a practical representation of the distribution systems for positive sequence studies. The primary objective is to capture the voltage drop in distribution networks, particularly under transient conditions.

Impedance of a typical bulk-power delivery transformer is 8% on self-cooled MVA rating. A transformer is usually loaded above its self-cooled rating during peak load conditions, could be 110 to 140%. Many of bulk-power delivery transformers have Load Tap Changers (LTC). Typical LTCs and voltage regulators have 33 taps ( $0 \pm 16$ ) with each tap step 5/8%. This translates into  $\pm 10\%$  regulation range. Substation voltage is typically controlled to 124 V (on 120V secondary voltage base) with regulation dead-band of 2 to 2.5V. California utilities use Conservation Voltage Reduction (CVR) and keep distribution substation voltages close to 120V secondary. A typical delay for the first tap adjustment is 30 seconds after the distribution voltage is out of control band, and the time delay for

the subsequent adjustments ranges from 2 to 5 seconds. Switched capacitors are also used for voltage control and power factor correction, both at the substation and along the feeders.

The purpose of a feeder equivalent model is to capture the total voltage drop and real and reactive power losses in primary distribution circuits, distribution transformers, and secondary distribution circuits. Default impedance of  $R=0.04$  and  $X=0.04$  per unit is used in WECC. Software packages have checks built in for distribution profile and adjust feeder impedance to hold end-use utilization voltage above 95%.

## B) Models of Electrical End-Uses

It is essential to capture the diversity of electrical end-uses in the model, yet to keep the number of model components manageable. Composite load model has provision for four motor models, power electronic loads, as well as static polynomial loads. Southern California Edison and Bonneville Power Administration developed state of the art laboratories for testing end-use equipment. The labs include a programmable power supply capable of applying a wide range of voltage and frequency disturbances to electrical end-uses [3]. BPA and SCE tested residential and commercial air-conditioners, refrigerators, single and three-phase fans, water pumps, a wide spectrum of residential appliances. SCE also tested inverters used in solar PV installations. BPA and PNNL tested Energy Management Systems used in commercial buildings. For large motors, we used manufacturer's published data to develop model parameters.

WECC uses different data sets for "commercial" / "residential" substations versus "industrial" loads. For "commercial" and "residential" substations, which are majority of system load, the motor models represent the following:

- Motor A represents three-phase compressor motors in commercial cooling and refrigeration systems. Model data is representative of compressors used in roof-top systems in retail and office buildings. These motors are usually 5 to 25 HP compressor motors, special design with high starting torque. The driven load is constant torque on average. The motors will have contactors which drop out when voltage drops below 40-45% and reclose when voltage recovers above 45-55%.
- Motor B represents fan motors. Model data is representative of 5 to 25 HP NEMA type B motors. Fans tend to have higher inertia, from 0.25 to 1.0 second, and torque load proportional to speed squared. The recent trend is to use Electronically Commutated Motors (ECMs) in ventilation applications. ECMs are modeled as power electronic loads.
- Motor C represents pump motors, usually part of commercial building cooling systems. The data is similar to that of Motor B, except a smaller inertia, 0.1 to 0.2 seconds. Many of pump motors are now behind Variable Frequency Drives, and need to be modeled as power electronic loads. Motor C percentages are usually very small in the load model data used in WECC.
- Motor D represents single-phase compressor motors used in air-conditioning and refrigeration. WECC uses "performance" model to represent static relationship between voltage and active and reactive power consumed by a compressor motor. The model has "run" and "stall" states represented with static polynomials. The switch between the states is made based on the voltage. The model also includes thermal protection that trips motors after it heats up following stall.

The original compressor motor used "V<sub>tsall</sub>" and "T<sub>stall</sub>" parameters to switch from "run" to "stall" mode. Once a motor stalled, it remains stalled even when the voltage recovers. "V<sub>stall</sub>" of 60% and "T<sub>stall</sub>" of 2 cycles were used as default parameters based on the initial round of testing. However, recent tests done at BPA in collaboration with John Undrill and Bernie Lesieutre show that point on wave where fault is applied makes a big difference on whether a compressor motor rides through a fault or stalls. Tests and studies show that when a fault is applied at zero crossing, a large electrical braking torque develops, making compressor motor stall very fast. When a fault is applied at the crest an AC waveform, a compressor has a greater chance to ride through normally cleared faults. Another important factor is whether the voltage is stepped or ramped down (even one cycle ramp makes a difference). Compressor motors tend to stall when voltage drop is sudden, and more likely to ride

through when voltage is ramped down, even over a cycle. Analysis of actual fault recordings shows that the voltages does not drop instantaneously during a fault, but rather decays over a cycle or so because of the motor back-feed supporting voltages when a fault is applied. Compressor motor models are being revised to reflect this recent new information.

### III. COMPOSITE LOAD MODEL IMPLEMENTATION

Assumptions on load composition are paramount for dynamic load modeling. Load composition varies seasonally, hourly and with climate zones. WECC approach divides the interconnection into twelve climate zones. Within each climate zones, substations are designated as:

- Residential, representative of a sub-urban area
- Commercial, representative of down-town areas and office parks
- Mixed, a mix of residences and commercial areas
- Rural and agricultural.

In addition, many of industrial loads (e.g. petrochemical, paper mills, aluminum smelters, irrigation) have specific identifiers.

WECC utilities are now required to populate study base cases with climate zone information, which is a seven character identifier that includes a climate zone and substation type, for example “DSW\_COM” describes a “commercial” substation in Desert Southwest region, and “NWC\_RES” describes a “residential” substation in a coastal area of Pacific Northwest.

PNNL developed the original full-scale Load Composition Model. The model was very detailed and included comprehensive models of various types of residential (e.g. single-family detached and multi-family) and commercial (e.g. large office, grocery, retail, assembly, hotel, etc) buildings. The model was very instructive in understanding load profiles and load composition of various types of buildings and feeders. Commercial end-use survey performed by California Energy Commission had the most complete data sets for commercial building [11].

For production implementation, BPA developed a “light” version of the Load Composition Model. 24-hour load composition profiles were generated for normal summer, summer heat wave, shoulder and winter seasons for all 12 climate zones. Load Composition Model can plot load profile and composition for a chosen make-up of residential, commercial and industrial loads, Figure 2.

WECC technical staff compiles powerflow baselines and dynamic data used in power system studies. WECC staff has tools that link climate zone information with load composition and motor model data to produce composite load model records.

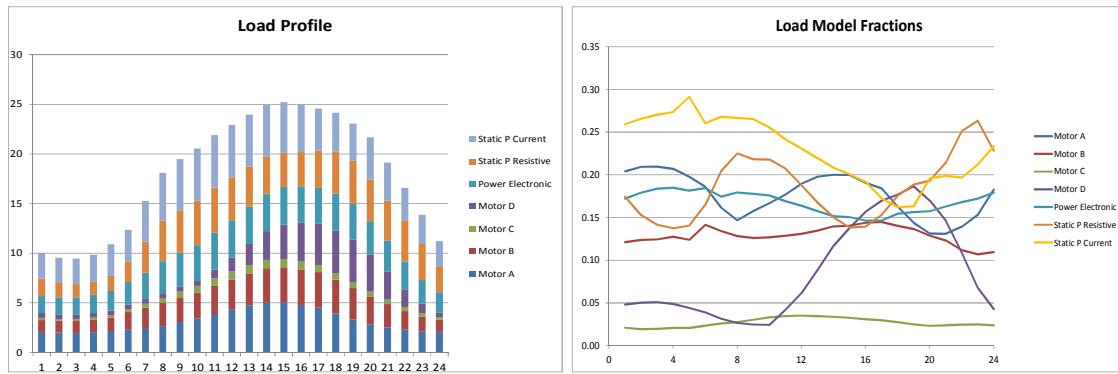


Figure 2: load shape and load composition from WECC Load Composition Model

#### IV. LOAD MODELS STUDIES

Model validation is essential for model acceptance.

BPA studies show that the composite load model improves representation of damping of inter-area power oscillations, Figure 3.

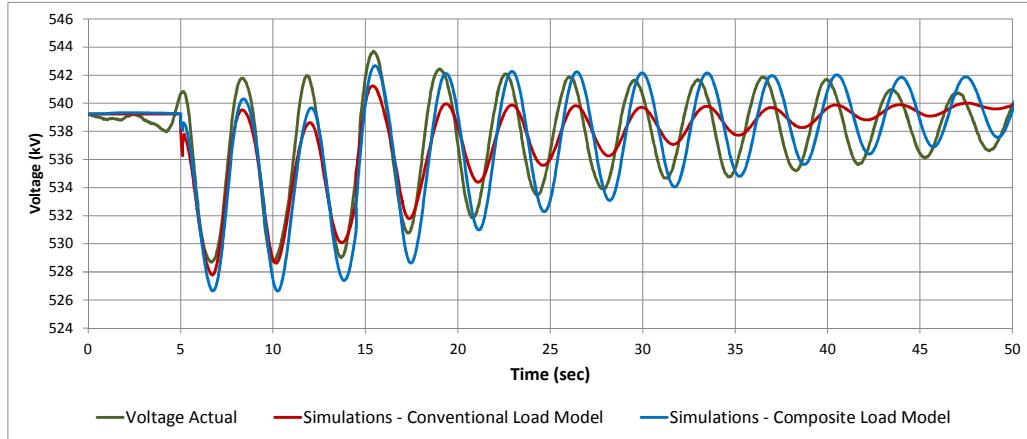


Figure 3: actual data and simulations of August 4 2000 inter-area oscillation event in Western Interconnection

Southern California Edison was successful in matching several FIDVR events observed in their system, Figure 4.

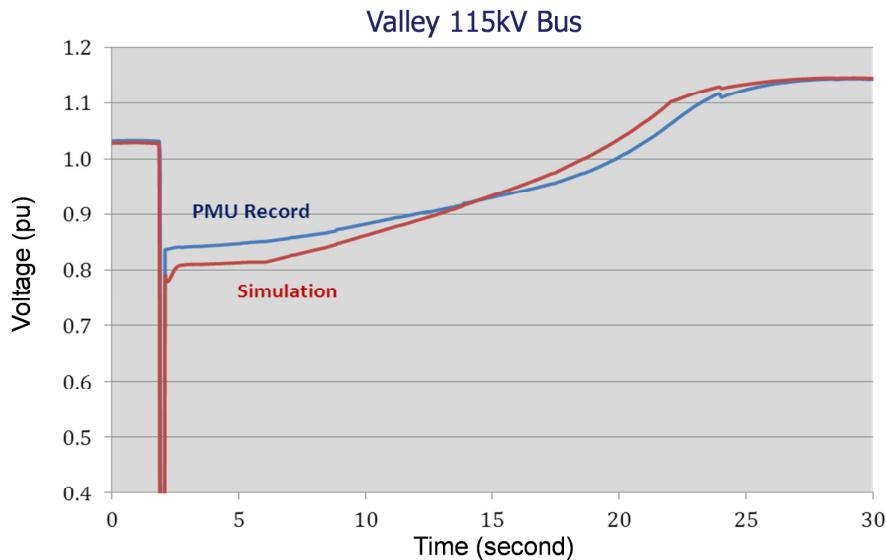


Figure 4: actual data and simulations of a FIDVR event in Southern California

A comprehensive set of system impact studies was done by operating entities within WECC during 2011-12. The studies were done with Phase 1 composite load model, where compressor motors were assumed to ride through system faults. The studies identified several model data issues, primarily related to motor protection settings, which have been since addressed.

Motor protection and amount of load loss during a fault continue to be relevant issues. There is evidence from actual events that a portion of voltage-sensitive load is lost during a fault. On July 29 2009, a multi-cycle fault in Utah area resulted in tripping of nearly 900 MW of voltage-sensitive load.

WECC continues research in the area of load voltage sensitivities by engaging industry experts. Report [11] provides initial guidance.

Starting 2014, all planning and operating base cases produced by WECC include the composite load model. The model is used in operating studies that set System Operation Limits and planning studies for compliance with NERC TPL-001 Transmission Planning Reliability Standards.

## V. PHASE TWO COMPOSITE LOAD MODEL

WECC Load Modeling Task Force continues its efforts to implement Phase Two of the composite load model:

A) Data management improvements:

Composite load model has 120+ parameters. Every load in the same climate zone has the same set of parameters. The same record is duplicated hundred's times just with a different bus header. We requested program developers to recognize the dynamic records using climate zone identifiers. This will reduce the number of records associated with composite load model from about 4,000 down to 60, thereby making the data more manageable.

B) Revisions to air-conditioner models:

The next version of the air-conditioner “performance” model will reflect the recent findings made by BPA, John Undrill and Bernie Lesieutre. Sensitivities with respect to motor stall parameters are encouraged.

C) Motor protection

WECC LMTF will continue working with building and motor protection experts to review protection models.

D) Distributed PV generation

The installation of distributed solar PV generation is on the rise in the southern part of the Western Interconnection. There is a strong need to model solar generation impact on power system dynamic performance. Southern California Edison has been leading the way by testing PV inverter responses to voltage and frequency disturbances. Appropriate models will be developed and integrated in the Phase Two composite load model.

E) Load Monitoring

Southern California Edison in collaboration with Lawrence Berkeley National Laboratory deployed a large number of power quality recorders in their distribution systems [9].

Distribution recordings combined with transmission level PMU recordings provide unprecedented synchronized view of load response to system faults, and essential part of the model validation and ultimate model acceptance.

## VI. ACKNOWLEDGEMENT

A number of engineers were involved in development of the composite load model:

- Anatoly Meklin, retired from Pacific Gas and Electric, was the key contributor to development and prototype of the composite load model structure.
- Many engineers in the Western Interconnection contributed to the adoption of the composite load model, including Eleanor Ewry at Puget Sound Energy, Eric Bakie at Idaho Power, Jeni Mistry at Salt River Project, and Irina Green at California ISO.
- Jennifer Williamson at BPA has been invaluable resource on issues related to end-use composition of various buildings, their Energy Management Systems, and current trends in energy efficiency. Ryan Quint at NERC and Dean Latulipe at National Grid provided very constructive feedback on the composite load model use.
- Pavel Etingov and Yu Zhang at PNNL helped with Load Model Data Tool development and load composition analysis.

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