Modeling Stalled Induction Motors

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Abstract—**Southern California Edison experienced a slow voltage recovery event in summer of 2004 attributed to stalled air conditioning compressor motors. Simulations using existing load models was not able to reproduce the voltages recorded during the event. Based on tests of a four ton residential air conditioning unit a new model was developed to mimic the stall behavior of induction motors in order to replicate the voltage observed.**

I. Introduction

Load composition is a significant component in producing representative dynamic simulations for abnormal conditions on transmission systems. In particular, the response of induction motor load to low voltage events such as faults. In general, Western Electric Coordinating Council (WECC) cases represent load as 20% induction motor with the remaining load composed of differing percentages of constant impedance, constant current, and constant power.

Southern California Edison (SCE) experienced an event in summer 2004 which demonstrates the limited predictive value of existing load assumptions during low voltage events. A fault on SCE's Valley 115 kV system which cleared normally in four cycles caused voltages to sag for approximately thirty seconds.

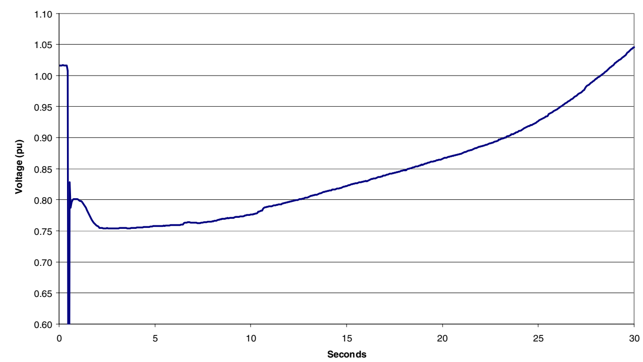
Simulations with existing models could not reproduce this response. A new load model was developed primarily based upon an Institute of Electrical and Electronics Engineers (IEEE) paper published in August 1992 titled "Transmission Voltage Recovery Delayed by Stalled Air Conditioner Compressors". The paper suggests that induction motors which drive the compressor of air conditioning (A/C) units can stall during low voltage events and cause sustained low voltages on the transmission system.

The new load model was benchmarked against the summer 2004 event. Though the new load model contains some simplifying assumptions, the predictive ability of the new load model does represent a step forward in representing induction motor load.

II. Event Description

During summer of 2004 a 115 kV bus connection component at SCE's Valley substation failed resulting in a fault. The fault cleared in four cycles isolating the number three 500/115 kV transformer bank. The remaining two 500/115 kV transformer banks stayed on-line. Voltage at Valley 115 kV was low for approximately thirty seconds, dropping to a minimum of about 0.75 pu. Figure 1 is a plot of the voltage during the first thirty seconds.

FIGURE 1
VALLEY 115 KV - THIRTY SECOND PLOT



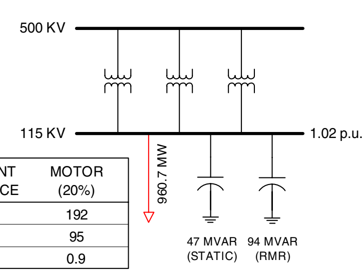
The event occurred on a Saturday with a high temperature of 80 degrees Fahrenheit in Los Angeles. Valley substation is located approximately 75 miles southeast of Los Angeles in an area expected to have higher temperatures relative to Los Angeles. It is likely that a large percentage of the Valley substation load were residential and commercial A/C. Immediately prior to the fault Valley substation recorded a load of 960.7 MW of which 400 MW was lost during the event.

The sustained low voltage is suspected to be caused by stalled induction motors in residential A/C units and the 400 MW lost is the result of the built-in protection of both residential and commercial/industrial A/C units.

III. Existing Load Model

Valley has three transformers connecting the 500 kV and 115 kV buses. There are also two sets of shunt capacitors on the Valley 115 kV bus and a load of 960.7 MW which represents the total load immediately prior to the fault. Figure 2 shows a diagram of Valley substation.

FIGURE 2
EXISTING LOAD MODEL
VALLEY (07/24/04)



	CONSTANT POWER (48%)	CONSTANT IMPEDANCE	MOTOR (20%)
MW	461	308	192
MVAR	0	0	95
PF	1.0	1.0	0.9

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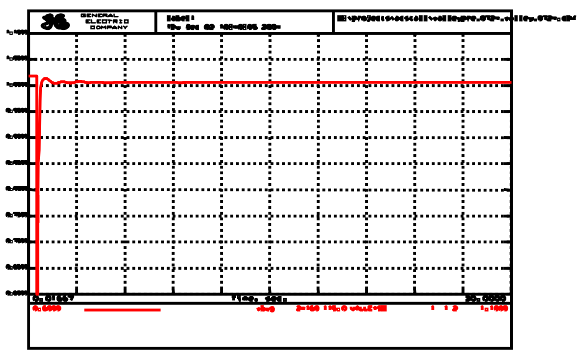
The allocation of motors at 20% of total load and motor behavior during dynamic simulations is determined by the MOTORW model of the GE PSLF program. It should be noted that the authors of MOTORW state that this model “is not appropriate . . . for situations where it may be necessary to simulate the stalling of motors”. Representing motors at 20% of total bus load across WECC is based upon an IEEE paper published in 2002 titled “An Interim Dynamic Induction Motor Model for Stability Studies in the WSCC”. The BLWSCC model governs the allocation of the remaining load at Valley as constant impedance, constant current and/or constant power. At Valley substation no load was allocated to constant current.

Figure 3 is a thirty second simulation using the existing load model. A three phase fault applied at 0.5 seconds with the fault and number three 500/115 kV transformer removed four cycles later. The voltage recovers very quickly after the fault clears and bears little resemblance to the thirty second voltage plot of the actual event in Figure 1.

FIGURE 3
SIMULATION OF EXISTING LOAD MODEL



IV. NEW LOAD MODEL

The assumptions used in the development of a new load model is based upon an IEEE paper published in August 1992 titled “Transmission Voltage Recovery Delayed by Stalled Air Conditioner Compressors” which documents the testing of a four ton residential central A/C unit. (Tonnage used in refrigeration refers to the amount of energy an A/C unit can move over a period of time. A one ton A/C unit can move 200 BTU/min. Residential A/C units range in size from a five ton central A/C unit to fractions of a ton for window models.)

Tests showed that the A/C unit will decelerate and stall at fault voltages below about 0.6 pu independent of fault clearing time. The test results were also used to develop a circuit diagram of the A/C unit (Figure 3 of IEEE paper). The circuit diagram was not explicitly used to represent induction motors under all conditions but instead a series of induction motor curves were developed to focus only on the behavior of the motor as it stalls. Only two elements were used in the new load model, the power factor and current. The power factor is only dependent upon the speed of the induction motor and does not vary with voltage. The current, however, varies with both speed and voltage.

Figure 4 shows the induction motor’s power factor at all speeds. Starting from a power factor of 0.88 at normal operating speed of 0.95 a voltage dip of less than 0.6 pu decelerates the induction motor toward 0.00 speed and a final power factor of 0.58. Tests were performed with the induction motor stalling against a stiff and weak system. A stiff system stops the induction motor in one cycle whereas a weak system stops the motor in 18 cycles. The new load model uses the average of the stiff and weak system and stops the induction motor in 9.5 cycles.

FIGURE 4
POWER FACTOR

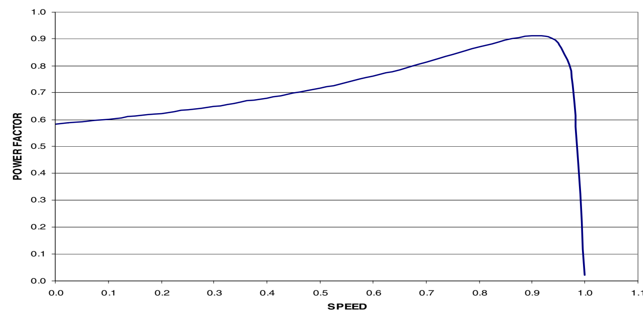
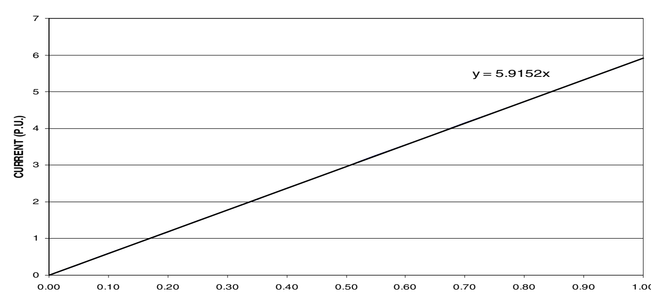


Figure 5 is a plot of the current and voltage relationship when the induction motor is in stall mode (0.00 speed). The current drawn by a stalled induction motor is also known as locked rotor current and is linear with the voltage. The new load model simplifies the coding by only representing the locked rotor current. The instant voltage drops below 0.6 pu only the locked rotor current is represented. Tests showed that it takes several cycles to stop an induction motor and therefore the current should ramp up to locked rotor current. This simplification produces a worse case result since locked rotor current is the largest current drawn by a stalled induction motor.

FIGURE 5
LOCKED ROTOR CURRENT



The impact of a stalled induction motor can be calculated from the power factor and locked rotor current characteristics. As an example, consider a 2.00 KVA A/C unit with its terminal voltage held at 1.0 pu. The amount of real and reactive power drawn at normal operating speed and at locked rotor (stalled) will be as follow:

	Normal	Stalled
Complex Power	2.00 KVA	11.83 KVA
Power Factor	0.88	0.58
MW	1.76 KW	6.86 KW
MVAR	0.95 KVAR	9.64 KVAR

The increase in both real and reactive power is very large but it should be noted that the voltage is assumed to be held at 1.0 pu. As the summer 2004 event demonstrates the system voltage tends to sag when a significant amount of A/C units stall. The large increase in both real and reactive demand drags the voltage down but as the voltage drops the amount of real and reactive power drawn by the stalled induction motor also decreases until the system reaches a steady state voltage. This state is disturbed by the built in protection devices for A/C units.

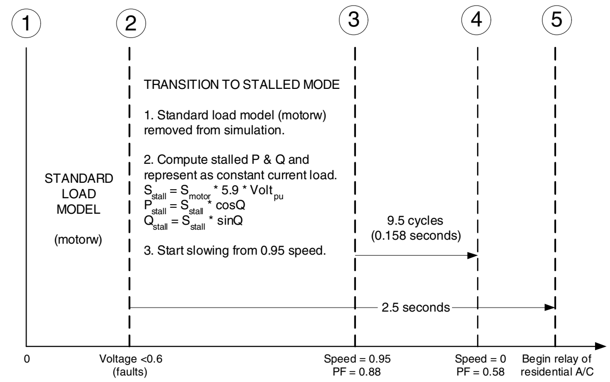
The IEEE paper also documents two classes of built in protection devices for A/C units. Large three phase A/C units, primarily associated with commercial or industrial cooling have undervoltage relays which can remove a stalled unit within cycles. The new load model removes three phase motors from the system six cycles after the voltage drops below 0.6 pu.

The other class are thermal relays with an inverse-time overcurrent characteristic used primarily in residential A/C units. These relays are much slower than undervoltage relays and operate in the seconds time frame. It would be impractical to represent several hundred thousand A/C units individually since each thermal relay may have different inverse-time overcurrent characteristics. These characteristics may depend upon the size of the A/C unit they protect, model, manufacturer, vintage and terminal voltage during the fault. The terminal voltage can vary because residential A/C units are found throughout a distribution system and their electrical separation can produce varying voltages particularly during a fault.

The new load model aggregates all residential A/C units and represents them as a single unit. Small percentages of this aggregated unit is removed over time to mimic the behavior of the thermal relays. The point at which residential A/C units begin to relay (2.5 seconds) and the percentage removed over time were adjusted to match the voltage profile exhibited during the summer 2004 event.

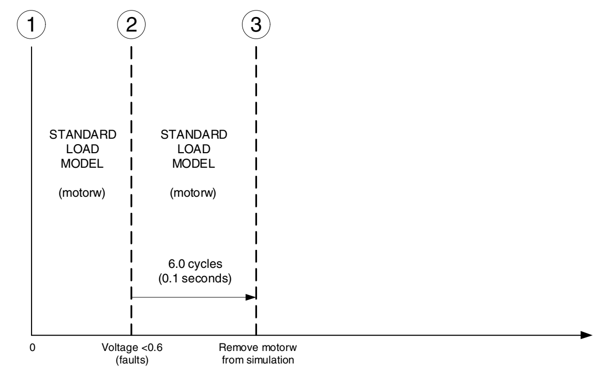
Figures 6 and 7 summarizes the behavior of the residential A/C and three phase motors. In Figure 6, the residential A/C unit is represented as MOTORW until the voltage dips below 0.6 pu at point 2. As the induction motor load transitions to stalled mode, the MOTORW model is removed and replaced by a constant current load computed based on the size of the induction motor, bus voltage, and a power factor of 0.88. The simulation time between point 2 and 3 is zero. From point 3 with a speed of 0.95 the induction motor is brought to a stop in 9.5 cycles at point 4 with a power factor of 0.58. At point 5, 2.5 seconds after the fault residential A/C units start to relay on overcurrent.

FIGURE 6
RESIDENTIAL AIR CONDITIONING
DYNAMIC MODEL



In Figure 7, three phase A/C units are represented using the MOTORW model and remains so until six cycles after the voltage dips below 0.6 pu. At point 2 when the voltage dips below 0.6 pu the new load model waits for six cycles till point 3 and removes the three phase motors from the simulation.

FIGURE 7
THREE PHASE MOTORS
DYNAMIC MODEL



The inertia for residential A/C and three phase motors are represented differently during the part of the simulation in which they are represented as MOTORW. No changes were made to the MOTORW model for residential A/C units and the inertia was left at the default value of 0.5. The inertia was increased from 0.5 to 2.0 to represent the larger three phase motors.

Figure 8 shows a one line diagram of the new load model along with the load composition at each bus. Three new buses were modeled to represent the 12 kV and 240 V system at Valley. The transformer reactances were set at 0.02 pu and resistance adjusted so subtransmission and distribution losses totaled approximately 5%. Additional shunt capacitors which represents subtransmission and distribution capacitors were also installed to bring the voltage near 1.0 pu at the 115 kV, 12 kV and 240 V buses. The residential A/C load is placed on a separate bus for clear identification during the simulation. The percent residential A/C (27%) and three phase motor load (15%) were derived by adjusting the amount of each load type until the voltage plot matched the summer 2004 event. No other combination of residential A/C and three phase motor load was able to produce a voltage of 0.75 pu immediately after the fault cleared. The remaining load allocation (constant power and constant impedance) was determined by the BLWSCC model.

FIGURE 8
NEW LOAD MODEL
VALLEY (07/24/04)

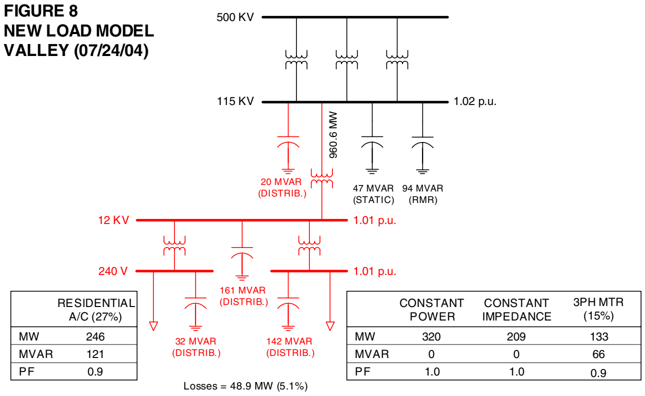


Figure 9 is a thirty second simulation of the new load model. A three phase fault was applied at 0.5 seconds with the fault and number three 500/115 kV transformer removed four cycles later. The voltage at Valley 115 kV recovers to about 0.75 pu after the fault clears and takes approximately thirty seconds to reach nominal.

FIGURE 9
SIMULATION OF NEW LOAD MODEL

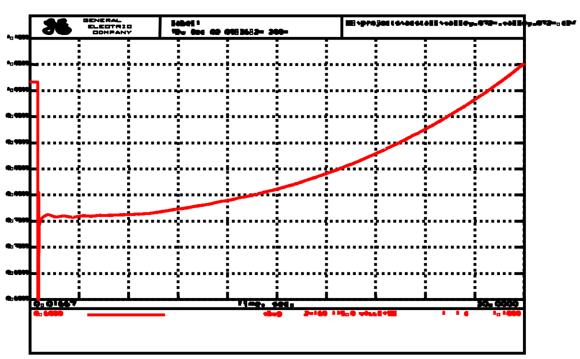


Figure 9 is very similar to Figure 1 except immediately after the fault clears. The voltage plot of the summer 2004 event shows the voltage recovering to 0.80 pu after the fault clears and then tipping over to 0.75 pu in a little more than one second. It is hypothesized that this is caused by residential A/C units caught at a critical time in their compression stroke.

As voltage drops the torque available from the induction motor to drive the compressor also drops. When voltage drops sufficiently low the induction motor is unable to overcome the pressure in the compressor and stalls. During a compression stroke the pressure is not constant and if the pressure in the compressor is low then even at low voltages the induction motor may still be able to drive the compressor for a short duration, at least until the pressure builds past the torque available and the motor stalls a fraction of a second later. The simulation has a more severe voltage performance by not representing this effect and should be considered a worse case scenario.

V. SUMMARY

The inability of existing load models to simulate the summer 2004 event demonstrates that current dynamic load models are not adequate to represent the stall behavior of induction motors. The new model only reproduced the stall behavior of a four ton residential A/C unit. Much more testing of A/C units and development of motor models will be required to arrive at an acceptable representation of the stall behavior of induction motors.

Developing an accurate model will be a complex task. A generator, transmission line, or transformer bank can be readily modeled because their parameters are specified when ordering or tested during commissioning and tends to remain fairly constant over time. The composition of load, however, is constantly in flux and somewhat of a mystery since it is dictated by many factors outside the control of the electric utility (i.e. appliance manufacturer techniques, economic conditions, land zoning, cultural trends). However, utilizing the following assumptions provided a starting point in the development of a load model to represent stalling behavior of induction motors:

1) All induction motors stall at 0.6 pu regardless of the duration of the voltage dip.

2) In aggregate, residential A/C in stalled mode behaves in a manner similar to a four ton central A/C unit.

3) Stalled three phase motors are removed from the grid in six cycles using undervoltage relays.

4) The equivalent inductance between 240 V and 12 kV is 0.02 pu. The equivalent inductance between 12 kV and subtransmission voltage (66 kV & 115 kV) is also 0.02 pu. Equivalent resistance in the subtransmission and distribution system produce losses of approximately 5%.

VI. BIOGRAPHIES

Garry Chinn. Garry is a Senior Power System Planner with Southern California Edison working in the Transmission & Interconnection Planning group. Garry graduated from the University of Southern California with a masters degree in Electrical Engineering. He holds a Professional Engineer license in electrical engineering from the state of California.