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Generation of Composite Load Protection Profiles for Reliable System Operation

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***Abstract*—Motor loads are equipped with protective mechanisms to prevent any damage to the loads in the event of a fault. Accurate representation of dynamic motor loads and their protection schemes is vital for power system planning and operation, especially in understanding system's response moments after a fault has occurred. Existing load models are inadequate to capture the behavior of protection mechanisms which can vary widely between different end-use appliances. This article proposes a methodology to generate composite protection profiles for commercial building motor loads. Combining knowledge of various protection schemes available in various end-use appliances, with the commercial buildings survey data (from U.S. Energy Information Administration) and typical end-use profiles generated using EnergyPlus™), composite load protection profiles were generated at one-hour interval over a year, for different commercial buildings in representative cities from different climate zones.**

***Index Terms*—Composite load model, protection model, commercial building.**

I. Introduction

Accurate modeling of load components is critical in reliable operation and planning of bulk power systems [1]. Traditional constant impedance (Z), constant current (I), or constant power (P) load models (abbreviated as ZIP) fail to capture the electromechanical behavior of modern motors and load-protection devices in the moments after a fault occurs on the power system. In an early effort towards high-fidelity load models for power systems simulation studies, EPRI developed component-based load models using load class and composition data [2]. An "interim" load model [3] was developed to address critical operational issues of the California-Oregon Intertie. However this model is inadequate to represent the Fault-Induced Delayed Voltage Recovery (FIDVR) phenomenon [4] due to its structural limitations [5]. FIDVR events have been increasing in Southern California and Florida [6] over the past several years. The fact that FIDVR events (in Fig. 1 [7]) are not well represented in power system studies has increased interest in load modeling, particularly of loads with a high penetration of motors, because dynamic load behavior profoundly influences the system dynamic response. A composite load model for dynamic simulations has been developed [5], and used in both planning and operation in Western Electricity Coordinating Council (WECC) in United States.

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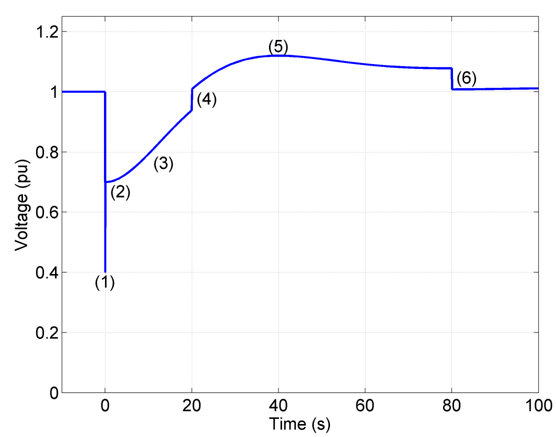

Fig. 1: Typical FIDVR event: initial fault (1), voltage recover and motor stall(2), thermal tripping (3), voltage control up (4), voltage overshoot(5), voltage control down(6)

The existing models are, however, inadequate to capture the behavior of modern motors or their load protection mechanisms in the moments after a fault, especially during a FIDVR event. The load protection used in the models is generally oversimplified and tends to either under-respond or over-respond. The fractions of the motor loads in the composite load model vary based on different regions, seasons and day types. In addition, for different building types, the motor types vary significantly with corresponding protection schemes [8]. Therefore, a composite protection model is needed to aggregate the performance of the protection of all the motor

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loads in the composite load model.

This paper presents a procedure to generate aggregated protection profiles in one-hour interval in one year, for different commercial buildings in representative cities from different climate zones. With the measured load profile of each commercial building, fraction of each appliance in the corresponding building type is calculated, based on the estimated power consumption values using buildings design protocols. The fraction of each protection type is then obtained based on the loading of the appliance motors. Finally, the composite protection profile in each climatic region is created by aggregation of protection profiles across all building types, based on their floor-space ratios. Section II of this paper describes the motor types and the corresponding protection schemes given in the WECC composite load model, as well as the protection for commercial buildings. Section III introduces the steps to generate load profiles and protection profiles for each commercial building type, and illustrates the generation of composite protection profiles for aggregated buildings. The paper is concluded in Section IV.

This work is part of a U.S. Department of Energy (DOE) Grid Modernization Laboratory Consortium (GMLC) project to develop a set of regional-level, scalable open source load models and tools [9]. While this paper focuses on the methodology for developing composite protection profiles, efforts are ongoing under the same project to analyze via simulations what impact the different composite protection profiles have on the system dynamics [17], [18].

II. Protection Methods

A. Background

There are four types of electric motors in the WECC composite load model, referred to as the motor type A, B, C or D [5]. This paper does address motor that are powered by variable frequency electronic drives. The motors correspond to the following load characteristics: 1) **Motor A**: Three phase (3-Φ) induction motors that operate under constant torque. Examples of such motors include air-conditioners and refrigerators in large commercial buildings; 2) **Motor B**: 3-Φ induction motors with high inertia, operating under speed-dependent torque. Example includes fan motors in residential and commercial buildings; 3) **Motor C**: 3-Φ induction motors with low inertia, operating under speed-dependent torque. Example includes pump motors in commercial buildings; and 4) **Motor D**: 1-Φ induction motors. Examples include residential and small-commercial air-conditioners and heat pumps.

Motors are typically protected by multiple devices, such as relays, contactors, thermal protection, etc. During a fault, as the voltage drops below a certain limit for longer than a certain duration, multiple protection mechanisms are triggered to trip the associated motor load. Fig. 2 illustrates how an aggregate motor load may respond during voltage event, due to the various protection schemes activated over the duration of the fault (Fig. 2 ignores the motor dynamics, but focuses only on the effect of the protection). Understanding the behavior of motor loads under the action of different protection schemes is of paramount importance. The goal of this work is to develop composite load protection models for the residential, commercial and industrial sectors, and integrate them in the Load Modeling Data Tools [10] software package. The focus of the work presented in this paper is on the commercial sector, while the residential and industrial sectors will follow later.

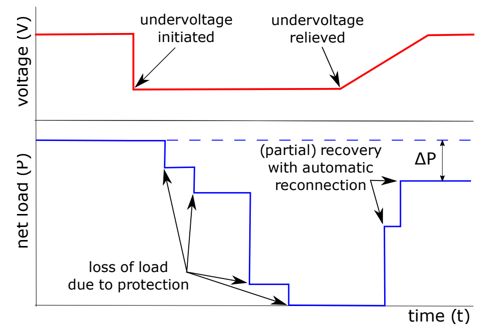

Fig. 2: Typical load tripping profile.

B. Protection schemes

The protection equipment present in different motors vary widely in their operating parameters (i.e. tripping and reconnection behavior). Furthermore, the response parameters of a protection device may not be static, and can also depend on factors such as the loading on the motor (e.g. fully loaded motors will likely trip earlier than lightly loaded motors), which may in turn depend on conditions such as the outside air temperature, occupancy of a buildings, etc. Modeling the protection schemes in a general way, therefore, is a challenging task.

To illustrate the modeling of the protection schemes, Fig. 3 depicts the parameters of electronic relays for example. The red area labeled as "100% Tripped Zone" is where it has been identified that the motor protection would most likely be activated and the motor taken offline. The white area labeled "Operating zone" is where it has been identified that the motors will continually operate through the voltage variance with no protection activated. The orange area labeled "Tripping Zone" indicates the area in which the protections on some fraction of the motors, such as the ones that are heavily loaded, are likely to be activated. The figure shows that if the voltage falls below 80% the protection trips almost instantly, for 100% of the motors that have electronic relays, while the heavily loaded motors can start tripping when the voltage drops below 90%.

Motor protection schemes commonly found in the commercial buildings in United States can be categorized into five different types, each of which is characterized by a range of voltage deviations and durations for tripping after the fault, and a range of voltage deviations and durations for reconnection during recovery. The different categories of protection are as follows:

1) **Protection 1 (or, Electronic Relays)**: These devices monitor incoming voltage to the motor. When a critical

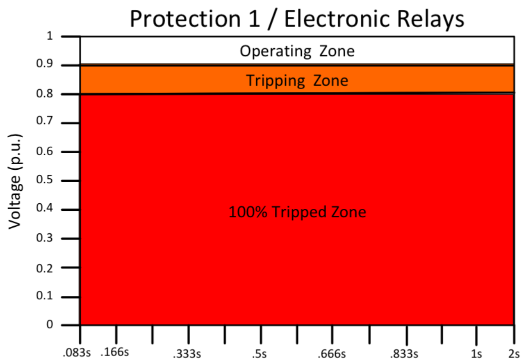

Fig. 3: Protection parameters for electronic relays.

fault condition (phase loss or phase reversal) is present, the relay will immediately de-energize the contactor thus dropping the motor voltage. These devices have user defined trip parameters but the device default settings apply to most applications and most devices are left to the recommend manufacture trip settings.

2) **Protection 2 (or, Current Overload Relays)**: When excessive current flows through the motor circuit, the relay opens due to increased relay temperature or sensed overload current, depending on the relay type.
3) **Protection 3 (or, Thermal Protection)**: These devices rely on excessive motor winding or motor case heat to trip a mechanical bimetal disk. These devices may be mounted internally next to the motor windings or externally on the motor or compressor casing. These are used in single phase applications only.
4) **Protection 4 (or, Contactors)**: These devices are not used as protection or safety devices for motors; but they do play a role in how and when a motor may disconnect and reconnect from the grid. Most motors are protected in some way. The few motors that are not protected or may have their motor protection adjusted incorrectly or bypassed completely.
5) **Protection 5 (or, Building Management System)**: these devices are not used as overcurrent or under voltage protection for motors; but they do play a role in how and when a commercial motor may disconnect and reconnect from the grid. These devices are generally computerized and when supply power is varied enough, the control system will proceed through a reboot process. During that time the motors under its control will be shut down (This is generally building wide).

C. Protection of commercial buildings

Our previous study [8] carried out research on the different protection schemes found in various commercial building types. The findings of that report were used to generate a "Protection Table" listing the available motor protections into the five different types defined above.

Table. I shows an example of such a table for retails buildings, where the P1 to P5 refers to the protection types

TABLE I: Retail building motor protections.

Building	Space [sf]	Appliance	Equipment	Type	Protection P1	P2	P3	P4	P5	Aggregate
Small Retail	10000	RTU	Fan	MB	0	1	0	1	1	P2P4P5
Small Retail	10000	RTU	Compressor	MA	0	1	0	1	1	P2P4P5
Small Retail	10000	RTU	Frac_Condensor	MD	0	0	1	1	1	P3P4P5
Small Retail	10000	Exhaust	Frac_Fan	MD	0	0	1	1	1	P3P4P5
Small Retail	10000	RiRF	Frac_Compressor	MD	0	1	0	1	0	P2P4
Small Retail	10000	RiRF	Frac_Fan	MD	0	0	1	0	0	P3
Small Retail	10000	WiRF	Compressor	MA	1	1	0	1	0	P1P2P4
Small Retail	10000	WiRF	Frac_Fan	MD	1	0	1	1	0	P1P3P4
Medium Retail	25000	RTU	Fan	MB	0	1	0	1	1	P2P4P5
Medium Retail	25000	RTU	Compressor	MA	0	1	0	1	1	P2P4P5
Medium Retail	25000	RTU	Frac_Condensor	MD	0	0	1	1	1	P3P4P5
Medium Retail	25000	RTU	Frac_Ind_Draft	MD	0	0	1	1	1	P3P4P5
Medium Retail	25000	Exhaust	Frac_Fan	MD	0	0	1	1	1	P3P4P5
Large Retail	75000	RTU	Fan	MB	0	1	0	1	1	P2P4P5
Large Retail	75000	RTU	Compressor	MA	0	1	0	1	1	P2P4P5
Large Retail	75000	RTU	Frac_Condensor	MD	0	0	1	1	1	P3P4P5
Large Retail	75000	RTU	Frac_Ind_Draft	MD	0	0	1	1	1	P3P4P5
Large Retail	75000	Exhaust	Frac_Fan	MD	0	0	1	1	1	P3P4P5

and the numbers 0 and 1 are used to represent absence and presence of that protection, respectively. In this example, the small retail building (with a typical floor-space of 10,000 square feet) has different appliances roof-top units (RTU), reach-in refrigerators and freezers (RiRF), walk-in refrigerators and freezers (WiRF) and exhaust fans, with various motors (e.g. fan motors, compressors, fractional compressors and condensers, etc.). Each such motor is equipped with a set of protection methods (assigned a value 1). Such tables are built for the following types of commercial buildings: 1) Retail (small, medium, large); 2) Supermarket; 3) Fast food; 4) Office (small, large); 5) Hotel/Lodging; 6) Warehouse; 7) School; 8) Hospital.

III. Generation of Load Profiles Profiles

This section presents the methodology used to develop the composite load profiles for aggregate protected motor loads.

A. Building Type Profiles

The first step in the process of generating the composite load protection profiles is to estimate the fractions of the commercial net end-use load consumption that are subjected to each type of protection. To do so, the loading on the different appliances in each building type is estimated, over a range of operating conditions defined by the seasons, time of day, and climatic region the building is in. This is done in two steps:

1) DOE EnergyPlus simulations [12] generate power consumption profiles of certain appliances in prototype building models
2) For appliances and/or building types for which EnergyPlus simulations are not available, the loading on the appliance motors is estimated, based on factors such as occupancy and outside air temperature.

DOEs Commercial Prototype Building Models [11] were used in this study to generate building electric load profiles. Whole building energy simulations were conducted by using EnergyPlus for 111 representative weather locations in 50 states in the U.S. The electric loads at individual equipment level are generated for 10-minute intervals over an entire year.

To estimate the power consumption of the motors and appliances, EnergyPlus simulations are used to obtain the power consumption for most of the appliances in the prototype buildings, such as the roof-top units compressors and supply fans. For other smaller motors, such as those in exhaust fans, dedicated outdoor air systems (DOAS) and make-up air units (MAUs), the power consumptions are estimated based on buildings design protocols [13]–[15]. A couple of examples are given below:

1) The exhaust fans used in the toilets are generally designed for air movement of 75 cubic-ft-per-minute (cfm) per fixture. The fan motors are typically rated at 1300 cfm/hp. Thus assuming a medium retail building of 25,000 sf of floor-space has 20 toilet fixtures, the exhaust fans are rated at 1.15 hp (or, 0.92 kW, with an efficiency of 0.8 kW/hp). Furthermore, the exhaust fans are expected to be running during the occupancy hours, which yield the desired power consumption profile for the exhaust fans.
2) The dedicated outdoor air systems (DOAS) that are found in hospital or large office buildings are designed to supply 5 cfm/person. Estimating the occupancies in a large office building of 500,000 sf at 2,500 persons, and in a hospital of 100,000 sf at 1,000 persons, the total air-movement through the DOAS can be estimated at 12,500 cfm and 5,000 cfm, respectively. An energy conversion factor of 300 cfm/hp yield the ratings of the DOAS fans in large office and hospital buildings as 41.67 hp and 16.67 hp, respectively. The DOAS also run during occupancy hours.

B. Protection profiles

Once the loading of the appliance motors is estimated at every time instant of any given day of the year, the net load fractions associated with each protection type can be computed for each building (Fig. 4 [left]). For example, if a building has n different motors, each of which is drawing a certain power $P_i(t)\,\forall i \in \{1,2,\ldots,n\}$, then the fractions of net building load at any given time t, that are assigned to any protection can be computed as:

$$\forall j \in \{1,2,3,4,5\} \quad \alpha_j^{\text{building}}(t) := \frac{\sum_{i=1}^{n} s_{ji}\, P_i(t)}{\sum_{i=1}^{n} P_i(t)} \ \forall t\,. \quad (1)$$

where the variables $s_{ji} \in \{0,1\}$, denote whether or not a particular protection type-j is present in the motor-i. Note that, for each building type, the protection fractions ($\alpha_j^{\text{building}}(t)$) can vary over time.

C. Aggregated profiles

Once the aggregation of appliance protection profiles are computed for each building (Fig. 4 [left]), the composite protection profile across all the building types is created. To do this, the presence of different buildings types across a (geographic/climatic) region is needed, either in terms of number or the total floorspace. The EIA Commercial Buildings Energy Consumption Survey [16] data provides us the total floorspace of each building type present in different geographic regions across the United States of America. This is done as illustrated in Fig. 4 [right]. For each building type, we scale the protection profiles by a scaling factor $w_{<\text{building}>}$ equal to:

$$w_{<\text{building}>} := \frac{\text{total floorspace of} <\text{building}>}{\text{floorspace of a prototype of} <\text{building}>} \quad (2)$$

and then take the sum across all building types weighted by this scaling factor $w_{<\text{building}>}$ (for each building).

D. Composite load profiles

With large amount of data to be analyzed and aggregated for different types of commercial buildings over one year in one-hour-interval, automated algorithm needs to be developed to generate the load profiles, as well as the protection profiles directly. In this work, a tool written in Python scripts were written to generate the results. The tool is composed of three main steps:

1) Aggregation of EnergyPlus simulation results
2) Profile generation of appliances, and fraction of protection types for each building
3) Aggregation of protection profiles across all building types

The tool in step 1 calculates the average building load profiles in one-hour-interval in each month for one year, based on the EnergyPlus simulation results. With the estimated loading on the different appliances in each building type in Section III-A, the tool in Step 2 generates the appliance profiles in each building in one year, as well as the corresponding fraction profiles of protection types. Based on the fraction of each building type in different geographic regions, the aggregated protection profiles for a combination of different building types are generated in Step 3.

The tool has been used to generate the aggregated protection profiles for commercial buildings in representative cities from 10 climate zones. These results are presented in a tabular form where the fractions of total load subjected to each protection method are calculated at an hourly basis for five typical days chosen to represent each different season of the year. Table. II shows a, example of such a table, for the commercial buildings in Phoenix, AZ, for a typical day in the month of January (winter season).

IV. Conclusions and Future Work

A detailed composite protection model is needed to study the aggregated protection performance of the composite load model, which is composed of different motor types and associated protection schemes. This paper introduces the procedure to generate the aggregated protection profiles for commercial buildings. A Python based tool is developed following the introduced procedure, to generate the protection profiles in 10 climate zones, in one-hour-interval for one year. This work lays a foundation for the future development of the composite protection model. The next step of this work is to validate the

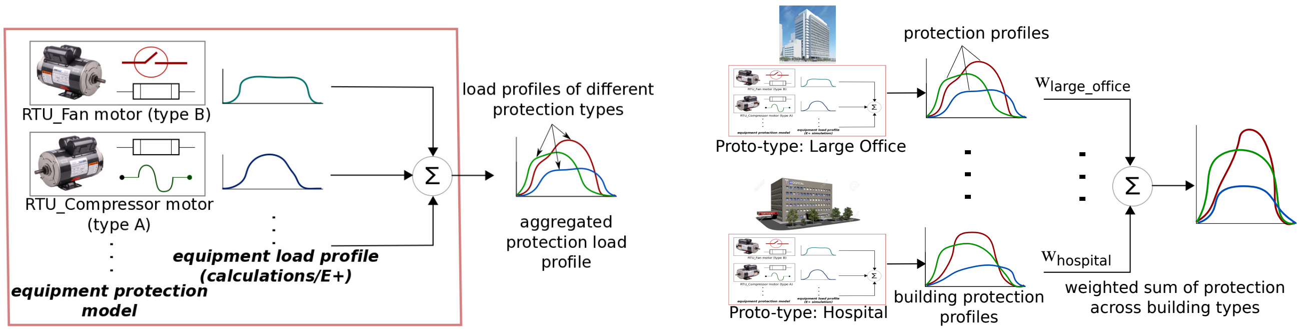

Fig. 4: [Left] Protection profiles for prototype building prototype. [Right] Composite protection profiles generated using the floorspace-based scaling factor defined by (2).

TABLE II: Composite protection profiles for the commercial building in January in Phoenix, AZ

Hour	Motor A					Motor B					Motor C					Motor D				
	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5
1	5%	11%	1%	15%	3%	3%	43%	0%	46%	41%	0%	7%	0%	3%	6%	1%	1%	31%	23%	20%
2	5%	11%	1%	15%	3%	3%	43%	0%	46%	42%	0%	7%	0%	3%	5%	1%	2%	31%	23%	20%
3	5%	11%	1%	14%	3%	3%	43%	0%	46%	42%	0%	7%	0%	3%	5%	1%	2%	31%	23%	20%
4	5%	11%	1%	14%	3%	3%	44%	0%	47%	42%	0%	7%	0%	3%	5%	1%	2%	31%	23%	20%
5	5%	10%	0%	14%	3%	3%	45%	0%	47%	43%	0%	7%	0%	3%	5%	1%	2%	31%	23%	20%
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20	10%	9%	2%	19%	10%	2%	45%	1%	48%	45%	0%	8%	0%	2%	7%	1%	2%	23%	18%	15%
21	9%	9%	2%	18%	9%	2%	46%	1%	49%	46%	0%	7%	0%	2%	6%	1%	2%	24%	18%	15%
22	9%	11%	2%	20%	8%	3%	42%	0%	45%	42%	0%	9%	0%	3%	7%	1%	1%	26%	20%	16%
23	6%	11%	2%	17%	5%	3%	41%	0%	44%	40%	0%	8%	0%	3%	6%	1%	1%	29%	22%	19%
24	6%	11%	1%	16%	4%	3%	42%	0%	45%	41%	0%	8%	0%	3%	6%	1%	1%	30%	22%	19%

developed protection profiles by simulation results in PSCAD and integrated transmission and distribution (T&D) dynamic co-simulation [17]. Voltage and frequency sensitivity studies will be performed. The simulation results will be used to validate the performance of the composite load model with updated protection profiles as developed in this paper.

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