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Modeling and Experimental Validation of Power Electronic Loads and DERs for Microgrid Islanding Simulations

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Abstract—Microgrid islanding can improve the reliability of distribution networks by enabling load to be supplied even after a fault has occurred nearby. The generation and load devices in microgrids are commonly interfaced by power electronics, causing a lack of inertia in the network. When microgrids transition from grid-connected to islanded operation after a fault, fast dynamics occur which have to be evaluated to assess stability during and after the transition. Their stability can be evaluated by time-domain simulations, however detailed and validated models of power electronic loads and distributed energy resources are required. This paper proposes component-based models of different types of power electronic loads, and single and three phase distributed energy resources. The models are validated with a variety of voltage and frequency transient experiments. A case study is performed where a modified version of the Cigre European LV residential network is islanded after a fault occurs. The results of the proposed, constant impedance and exponential load models are compared. The results indicate that the proposed models should be used for accurate analysis of the voltage and frequency stability during microgrid islanding simulations.

Index Terms—Microgrids, islanding, load modeling, dynamic models, distributed generation.

I. INTRODUCTION

FOR many years, islanding of electricity networks has been considered to be an unwanted situation in which the network should be de-energized as quickly as possible. In the last years, microgrids have become a topic of research which enable intentional islanding to increase the reliability of supply to critical loads in case of a network contingency. Fueled by the ongoing integration of distributed energy resources (DERs) and automated switchgear in distribution networks, recent literature proposes to extend this feature to distribution networks as well [1], [2]. Network codes and standards such as the IEEE 1547 are evolving to allow islanding by expanding the voltage and frequency ride-through of DERs, and describing the situations and requirements for intentional islanding.

When a fault occurs in a distribution network, part of the network may be islanded as a microgrid to supply the load while the faulted part of the network is being restored. During this fault-initiated islanding (FII), a sequence of three phases

takes place: fault, grid-feeding islanding and grid-supporting islanding. During the fault phase, the voltage decreases which makes it difficult for the phase-locked loop (PLL) of DERs to estimate the phase angle [3]. This may cause frequency deviations from nominal when entering the grid-feeding islanding phase, which is amplified by interactions between the PLLs and the load in the islanded network [4]. Additionally, the DERs provide no voltage control during the grid-feeding islanding phase which increases or decreases the voltage when the generation is larger or smaller than the load respectively.

To ensure reliable operation, the voltage and frequency stability during each phase of the islanding transient has to be critically evaluated before enabling FII. This evaluation has to be performed periodically due to changes in load connection, intermittent generation of DERs and varying state of charge of energy storage systems. Time-domain simulations can be performed to evaluate the transient stability, which requires detailed DERs and load models.

With higher penetration of power electronic interfaced DERs in the distribution network, the impact on network dynamics becomes larger. DERs can be modeled in different ways depending on the type of analysis [5]. As shown by [6], models which simplify or neglect the DC-link dynamics may prevent accurate stability analysis in some cases. Several DERs models have been proposed in the literature, however there is a lack of accepted and validated transient models [5]. During FII, anti-islanding protection can cause disconnection of generation which can significantly impact the islanding capability. Therefore DERs models used for FII simulations should describe the dynamic behavior during voltage and frequency changes, and anti-islanding protection. However this behavior of grid-feeding DERs models has not yet been validated during the large voltage and frequency transients which occur during FII.

In most power system studies, static load models such as constant impedance/current/power, ZIP or exponential models are used [7]. These load models provide adequate accuracy for steady-state or semi steady-state studies. However since the instantaneous power balance is critical in an islanded network, the transient dynamics and nonsinusoidal current waveform of the power electronic load devices should be more accurately represented than static load models.

Power electronic load devices are decoupled from the grid frequency by a DC-link connected by either a passive or active rectifier. This paper considers passive rectifier power

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electronic loads (PRPELs) since devices of this type are most abundant and have unique dynamics which can impact microgrid stability during islanding. During a voltage change in the network, the deviation between grid voltage and DC-link voltage causes PRPELs to have inrush or disconnection behavior. When the DC-link voltage becomes too low during a voltage dip, PRPELs can drop-off which can cause significant load changes during and after a voltage dip [8]–[10]. During drop-off, PRPELs switch off and the active and reactive power absorbed by the load is equal to zero.

The dynamics and current waveform of PRPELs are not described by static load models. However in recent literature, static load models [11]–[15] or static load models with dynamic directly coupled induction motor [16], [17] have been used for simulating islanding transients and assessing stability of islanded networks.

Component-based models can model the behavior of load devices with a high level of detail. The steady-state instantaneous current waveform and harmonic profile of component-based motor and electric vehicle charging load models has been successfully validated by [18], [19]. The dynamic behavior of a generic component-based PRPEL load model during a voltage dip has been shown by [8], indicating that the transient dynamics and drop-off behavior can be accurately modeled with component-based models. However, the proposal and experimental validation of component-based models of different PRPELs are so far lacking in the literature.

In this paper, component-based models of variable frequency drive (VFD), compact fluorescent lighting (CFL), light emitting diode lighting (LEDL), switched-mode power supply (SMPS) electronics, single phase PV (SPPV) and three phase PV (TPPV) devices are developed. The models are validated with experiments of physical devices under large voltage and frequency transients. The validated models are used in a FII case study of a representative low voltage microgrid and the results are compared to results with static load models to showcase the need for component-based models for islanding simulations.

The contributions of this paper are:

- 1) Component-based load models are defined which accurately describe the transient dynamics, current waveform and drop-off behavior of several typical PRPELs.
- 2) Single and three phase component-based grid-feeding DERs models are defined which accurately describe the large-signal dynamics and anti-islanding behavior of DERs.
- 3) Experimental validation of individual and combined component-based load and DER models during steady state and voltage and frequency transients is carried out.
- 4) The proposed, constant impedance and exponential load models are compared in a FII study case.

In the next section the component-based models are described. The models are validated in section III and used for a FII case study in section IV. The results of the validation and case study are discussed in section V and finally conclusions are given in section VI.

Fig. 1: (a) Compact fluorescent light model. (b) LED lighting model.

II. COMPONENT-BASED MODELS

Component-based models for several types of loads and grid-feeding DERs are presented in this section. The load models included in this paper describe the behavior of the most common PRPELs in low voltage networks i.e. CFL, LEDL, VFD and SMPS electronics [20]. The models include the components, drop-off behavior and protection systems which are most significant for microgrid transient simulations, including large voltage and frequency transients. The model parameters are determined by inspection of the physical devices and their data sheets, and parameter sweeping during the experimental validation as described in section III-A. The parameters values which have been determined by parameter sweeping and inspection are denoted by * and † respectively.

A. Load devices

1) *CFL and LEDL*: The CFL and LEDL models are shown in Fig. 1a and 1b respectively. The models have a different input filter, equivalent resistance and the LEDL model has a zener diode to regulate the voltage at $V_{zen} = 60V^*$ for the LEDs. High power LEDL may have a DC-DC converter stage to regulate the voltage as opposed to a zener diode for higher efficiency. LEDL and CFL loads can be modeled for steady state simulations as constant impedance and constant current loads, therefore the equivalent resistance can be described by equation 1a. The drop-off voltage of the DC-link is relatively low for both LEDL ($V_{off} = 50V^*$) and CFL ($V_{off} = 35V^*$). After drop-off the load will instantly recover when the DC-link voltage increases above the threshold.

$$R_{eqz}(t) = R_{dc}\alpha(t), \quad R_{eqi}(t) = \frac{V_{dc}(t)}{I_{dc}}\alpha(t) \quad (1a)$$

$$\alpha(t) = \begin{cases} 1, & \text{if } V_{dc}(t) \geq V_{off} \\ 0, & \text{otherwise} \end{cases} \quad (1b)$$

Where R_{dc} , I_{dc} are the nominal resistance and current, and V_{dc} is the DC-link voltage.

Fig. 2: Variable frequency drive model. SC: speed controller, DTC: direct torque controller.

Fig. 3: Switched-mode power supply model. CC: current controller, VC: voltage controller.

2) *VFD*: The VFD model consists of electrical, induction machine and controller parts as shown in Fig. 2. The three-phase inverter drives the induction motor using a direct torque controller (DTC) with space vector modulation (SVM). The DTC has controller gains $k_{pt} = 0.005^\dagger$, $k_{it} = 100^\dagger$. The speed controller has controller gains $k_{ps} = 10^\dagger$, $k_{is} = 4^\dagger$, torque reference saturation $T_{sat} = 72Nm^\dagger$, speed reference $\omega_{ref} = 157rad/s^\dagger$ and speed reference ramp $\omega_{rl} = 30.6rad/s^\dagger$.

The induction machine is modeled as the symmetrical induction machine model in the dq reference frame described by [21]. In this model, R_s, R_r denote the resistance and L_s, L_r denote the inductance of the stator and rotor respectively. Variable L_m denotes the mutual inductance. The mechanical part of the induction motor is described by equation 2, where ω is the rotational speed, and $T_m, J = 0.06543kgm^2^\dagger$ [22], $F = 0.035Nms^*$ are respectively the mechanical load, inertia coefficient and friction factor of the induction motor.

$$\dot{\omega} = \frac{1}{J}(T_e - F\omega_m - T_m) \quad (2)$$

The VFD has a DC undervoltage protection which operates when the DC-link voltage drops under the threshold value ($V_{off} = 420V^*$) with a hysteresis of $30V^*$. When the threshold is reached, the electrical torque reference value for the DTC is set to zero and the machine rotates until the rotational speed decreases to zero. When the DC-link voltage increases above the threshold value before the rotational speed is zero, the VFD will remain operational. If the rotational speed reaches zero, the DC undervoltage protection trips and the load is disconnected until manual reset.

3) *Generic SMPS electronics*: This model describes electronic loads which are fed by a SMPS. The model shown in Fig. 3 has active PFC provided by a boost converter which is controlled by voltage and current controllers. The normalized

Fig. 4: Single phase PV model. CC: proportional resonant current controller, PC: power controller, PLL: phase-locked loop, VC: DC voltage controller.

DC-link voltage at the rectifier (V_{dc1}) and the voltage after the boost converter (V_{dc2}) are measured and multiplied to provide a reference for the voltage controller to regulate the DC-link voltage at as described by [23]. The DC voltage reference is $V_{dcref} = 380V^\dagger$ [24]. The voltage and current controllers have proportional and integral gains $k_{pv} = 0.053^*$, $k_{iv} = 2.89^*$ and $k_{pc} = 0.102^*$, $k_{ic} = 4264^*$ respectively. The PWM switching frequency is $95kHz^\dagger$ and voltage V_{dc2} is filtered by a low pass filter with a bandwidth of $200Hz^\dagger$ [24]. If the DC voltage or current become higher than $410V^\dagger$ or $5.5A^*$ respectively the protection system trips, reducing the current reference of the PFC to $I_{ref} = 0$. The protection system has a hysteresis of $30V^\dagger$ and $0.5A^*$.

In a SMPS the DC-link voltage is strictly regulated to a constant value by a buck converter after the PFC stage. Therefore the equivalent resistance has a constant power characteristic which is described by equation 3, where P_{dc} is the nominal power.

$$R_{eqp}(t) = \frac{V_{dc}(t)^2}{P_{dc}} \alpha(t) \quad (3)$$

The drop-off voltage depends on the device which is connected to the SMPS. Experiments performed by [25] indicates that devices with a SMPS typically drop-off when the grid voltage is between 0.6pu and 0.3pu. The SMPS in this paper can regulate the DC-link voltage until grid voltage becomes smaller than 0.3pu. To evaluate the SMPS for voltages of 0.3pu and smaller the equivalent resistance is changed from constant power to constant impedance characteristic when the DC-link voltage drops below 30V.

B. Grid-feeding DERs

The grid-feeding SPPV and TPPV models are shown in Fig. 4 and 5 respectively. The single phase inverter is controlled by a proportional resonant (PR) controller in the $\alpha\beta$ reference frame, while the three phase inverter is controlled by a proportional integral (PI) controller in the dq reference frame. The maximum power point tracking dynamics are not taken into account due to the long time constant relative to the phenomena of interest. Therefore the primary source is modeled as a Thevenin equivalent. The SPPV and TPPS are described by [26]. The PI gains of the SPPV PLL are $k_{ppll} = 43.3^*$ and $k_{ipll} = 2792^*$, while the PI gains of the TPPV PLL are $k_{ppll} = 30.87^*$ and $k_{ipll} = 1029^*$.

MX45-3PI programmable voltage source. From these tests the voltage and frequency dependence during steady state, anti-islanding protection thresholds and shape of the current waveform are determined.

Voltage transient experiments are performed by supplying step changes from nominal voltage to a voltage in the range of 0.1pu to 1.1pu and back to nominal voltage after 200ms. Frequency transients are performed by step changes from nominal frequency to a frequency in the range of 20Hz to 80Hz and back to nominal frequency after 200ms. The initiation and recovery of the transients take place when the phase a voltage waveform is at positive peak value. The voltage and frequency transients represent a FII situation where the voltage and/or frequency is disturbed (i.e. by a fault and/or grid-feeding islanding) and is restored to nominal after some time. 200ms is deemed to be representative for a FII transient, however in practice the length of this period depends on factors such as the fault clearing time and islanding detection time. The mechanical load of the VFD is varied between 0% and 100%. The transient experiments allow to determine the dynamic voltage and frequency dependence, anti-islanding protection time settings and load drop-off time.

During the experiments the voltage and current waveforms are recorded using a Hioki PW6001 power analyzer. The voltage waveform $V_m(t)$ is provided as an input for Matlab/Simulink models of the devices described in section II with the parameters provided by the parameter sweep. All electrical components and controllers shown in Fig. 1a, 1b, 2, 3, 4 and 5 are included in the models from the SimPowerSystems and Simulink libraries. The current waveform of the physical devices $I_m(t)$ and models $I_s(t)$ are compared to determine the NMAE by using equation 8, where $\hat{I}_n$ is the peak value of the current waveform under nominal conditions. The NMAE is determined over a period of $T = 500\text{ms}$ which is 150ms before and after the transient period to take the pre- and post-disturbance performance into account. The set of parameters with the lowest NMAE is considered as the resulting model parameter set.

$$e(t) = \frac{1}{\hat{I}_n T} \int_{t=0}^T |I_m(t) - I_s(t)| dt \quad (8)$$

The current measurements are performed with Hioki CT6843-05 200A (SPPV), Hioki CT6841-05 20A (CFL, SMPS, TPPV, SMPS), Hioki 9661 500A (VFD) and Hioki CT6700 5A (LEDL) current clamps. The tested devices are:

- 2x Sylvania mini Lynx Fast (2x9W CFL)
- 2x GAMMA LED (2x1.2W LEDL)
- ABB ACS550 with ABB M2QA160M4A (11kW VFD)
- Corsair VS350 ATX power supply (350W SMPS)
- Soladin Web 3000 (3kW SPPV)
- SMA Sunny Tripower (8kW TPPV)

The primary source of the SPPV and TPPV is emulated by an Ametek TerraSAS photovoltaic simulator ETS (10kW). The mechanical constant torque load of the VFD is emulated by a ABB ACS850. To emulate the SMPS load, a 0.96Ω resistive load is connected to the 12V connection of the SMPS.

Fig. 7: Combined model validation setup. PVS: programmable voltage source, NMAE: normalized mean absolute error.

TABLE II: Normalized mean absolute error of component-based models during transient simulations. $V_{x,y}$: voltage step from nominal to x.y pu. F_x : frequency step from nominal to x Hz.

Case	CFL	LEDL	VFD	SMPS	SPPV	TPPV	COM
V1.1	0.031	0.011	0.027	0.056	0.044	0.020	0.035
V0.9	0.031	0.011	0.029	0.047	0.043	0.021	0.035
V0.7	0.031	0.010	0.028	0.058	0.050	0.034	0.038
V0.5	0.032	0.011	0.032	0.072	0.017	0.032	0.039
V0.3	0.035	0.012	0.035	0.113	0.013	0.035	0.047
V0.1	0.031	0.008	0.034	0.203	0.009	0.037	0.049
F80	0.028	0.021	0.021	0.038	0.016	0.154	0.076
F60	0.025	0.019	0.020	0.037	0.023	0.085	0.042
F40	0.025	0.018	0.022	0.038	0.021	0.079	0.048
F20	0.025	0.019	0.026	0.049	0.016	0.083	0.050

B. Combined Model Validation

To validate the accuracy of the proposed models under interactions between different devices, a combined validation is performed. In this case, all load and DER devices described above are connected to the same network and the aggregated current is measured during steady-state and transient testing as shown in Fig. 7. The LEDL and SPPV devices are connected to phase a, the SMPS is connected to phase b and the CFL devices are connected to phase c. The cables 1 and 2 in the network are 100m and 40m long underground cables of type 70mm^2 AL with a resistance and reactance of $0.623\Omega/\text{km}$ and $0.153\Omega/\text{km}$ respectively. Similar to the individual model validation, the recorded voltage waveform is provided to a Simulink network model. The network model consists of the models described in section II, while the cables are modeled as RL series impedance. The NMAE is calculated from the measured and simulated current by using equation 8.

C. Results

The model parameter values with the lowest resulting NMAE are given in table I. The NMAE of each device and transient simulation is given in table II, the combined validation is denoted by COM. The VFD results are produced with a mechanical load of 0.4pu. To discuss the accuracy of the models, comparisons between simulated and measured current waveforms during several transients are given in the remainder of this subsection.

The measured and simulated current waveforms of the CFL and LEDL during a voltage step from 1.0pu to 0.5pu and back to 1.0pu are shown in Fig. 8 and 9. Both of the models closely represent the physical load device during the voltage and frequency transient experiments.

Fig. 8: Measured and simulated current absorbed by the CFL during voltage transients to 0.5pu at $t_{on} = 0.42s$ and back to 1.0pu at $t_{off} = 0.62s$.

Fig. 9: Measured and simulated current absorbed by the LEDL during voltage transients to 0.5pu at $t_{on} = 0.42s$ and back to 1.0pu at $t_{off} = 0.62s$.

The result of the VFD during a voltage step from 1.0pu to 0.5pu and back to 1.0pu is shown in Fig. 10. The VFD does not absorb current during the voltage dip. When the voltage is recovered, an inrush transient occurs before the current recovers to steady state value. The modeled VFD shows transient dynamics which are similar to the physical device, however a deviation can be seen after the voltage recovery. The VFD will drop-off when the grid voltage is below 0.7pu for a duration which depends on the mechanical loading. At 20%, 40% and 60% or higher loading the drop-off time is 0.7s, 0.3s and 0.1s respectively for both the model and the physical device.

The current waveform of the SMPS model and physical device during a voltage transient from 1.0pu to 0.5pu back to 1.0pu is shown in Fig. 11. The dynamics of the model and physical device are very similar during voltage and frequency transients, however a deviation is present when the voltage steps back to 1.0pu. As shown in table II, the SMPS model has the highest accuracy when the grid voltage is larger than 0.3pu.

The result of the SPPV during a voltage transient to 0.5pu and back to 1.0pu is shown in Fig. 12. The anti-islanding detection trips at $t = 0.42s$ in both the model and physical device due to the undervoltage and at $t = 0.62s$ due to the voltage rate of change violation. The anti-islanding protection reduces the output to zero as described in section II. The SPPV model accurately represents the physical device during all transients as shown in table II.

The current waveform of the TPPV model and physical device during a voltage transient to 0.5pu and back to 1.0pu is shown in Fig. 13. The dynamics of the model and physical

Fig. 10: Measured and simulated phase a current absorbed by the VFD loaded at 40% during voltage transients to 0.5pu at $t_{on} = 0.42s$ and back to 1.0pu at $t_{off} = 0.62s$.

Fig. 11: Measured and simulated current absorbed by the SMPS with 150W load during voltage transients to 0.5pu at $t_{on} = 0.42s$ and back to 1.0pu at $t_{off} = 0.62s$.

device are similar during voltage and frequency transients. The anti-islanding voltage and frequency thresholds and time are validated to be equal to the values in table I.

The simulated and measured current waveforms of the combined devices during a voltage transient to 0.5pu and back to 1.0pu are shown in Fig. 14. The combined dynamics are closely represented by the models and as shown in table II the accuracy is similar to that of individual devices models. This indicates that the proposed models remain accurate when multiple models are used in the same network.

IV. CASE STUDY

A. Description

To compare the simulation results of static and the proposed load models, a modified version of the CIGRE European LV residential distribution benchmark network is analyzed [28]. Several empty nodes (no loads connected) of the network are removed, and DERs and an islanding switch are added as shown in Fig. 15. The battery energy storage systems (BESS) are intentional islanding capable [29]. The three phase (PV1) and the combined single phase (PV2) photovoltaic DERs both have a power rating of 50kVA. The cables of the network are of type 240mm² AL, modeled as series RL with an resistance of 0.15Ω/km and an inductance of 226μH/km. The cable length is given in table III.

Three different types of load models are analyzed in the case study: constant impedance, exponential and the proposed load models. The proposed DERs models are used in all cases. The loads and DERs connected to the network in each case are shown in table VI, note that in the case with the proposed

Fig. 12: Measured and simulated current injected by the SPPV during voltage transients to 0.5pu at $t_{on} = 0.42s$ and back to 1.0pu at $t_{off} = 0.62s$.

Fig. 13: Measured and simulated phase a current injected by the TPPV during voltage transients to 0.5pu at $t_{on} = 0.42s$ and back to 1.0pu at $t_{off} = 0.62s$.

load models a small part of the load is constant impedance load to represent a realistic load scenario.

Single phase loads and DERs are equally distributed over three phases. The models proposed in the last section are used by scaling the component values according to the power absorbed by the load. Constant impedance load models are based on the total power rating of the load connected to the nodes with a power factor of 0.95. As exponential load model the SimPowerSystems Dynamic Load is used. The active and reactive power absorbed by the exponential load are described by equation 9, where V_0 , P_0 , Q_0 are the nominal voltage, active power and reactive power. The Matlab Curve Fitting Toolbox is used to fit these equations to the active and reactive power measured during the steady-state testing described in section III-A and determine the voltage-dependence factors (a , b) shown in table IV.

$$P(t) = P_0 \left(\frac{V(t)}{V_0} \right)^a, \quad Q(t) = Q_0 \left(\frac{V(t)}{V_0} \right)^b \quad (9)$$

The same procedure is used with the sum of the active and reactive power of the loads connected to each node, to determine the voltage-dependence factors for the aggregated load. The aggregated factors are shown in table V. The BESS are modeled as TPPV which switches to grid-supporting control when the anti-islanding protection system is tripped consecutively when $t_{aa} \geq t_{sw}$. A voltage controller and droop power controller (voltage-active power/frequency-reactive power) are added to provide voltage and frequency control during islanding as described by [30]. The proportional and integral voltage controller parameters for both BESS are $k_{pv} = 0.37$, $k_{iv} = 241$. The active and reactive power

Fig. 14: Combined measured and simulated current absorbed by the devices in the network during voltage transients to 0.5pu at $t_{on} = 0.42s$ and back to 1.0pu at $t_{off} = 0.62s$.

TABLE III: Network cable lengths.

	1-2	2-3	3-4	4-5	5-6	2-7	3-8	4-9	5-10
Length (m)	70	35	70	105	70	30	135	30	30

droop controller parameters are $k_P = -\frac{8.125}{S_n} \text{V/kW}$, $k_Q = \frac{0.25\pi}{S_n} \text{rad/s/kVA}$ where S_n is the power rating of the BESS.

To evaluate the voltage and frequency stability during FII a sequence of a fault, islanding and control-mode switching is simulated in two scenarios. In both cases the PCC is initially closed (grid-connected operation) and all DERs are operating in grid-feeding operation. At $t = 0.1s$ a three phase fault is emulated by reducing the external grid voltage to 0.1pu and thereafter the switch at the PCC is opened, islanding the network. When the network is islanded, the voltage and frequency will deviate from nominal allowing the islanding detection of the BESS to trip and switch to grid-supporting operation.

In scenario 1 the BESS have a power rating of 110kVA with active power reference of 60kW during grid-feeding operation, the network is islanded at $t = 0.15s$ and the anti-islanding detection time is $t_{sw} = 0.2s$. In scenario 2 the BESS have a power rating of 150kVA with active power reference of 75kW during grid-feeding operation, the network is islanded at $t = 0.2s$, the PLLs have a five times higher bandwidth and the anti-islanding detection time is $t_{sw} = 0.3s$. The network is modeled in Matlab/Simulink and solved with a time step of $1\mu s$.

B. Results

The voltage waveform at node 6 in scenario 1 and 2 with constant impedance, exponential and the proposed load models are shown in Fig. 16 and 17. Since the cable distances are relatively short, the voltage is similar throughout the network. From the voltage waveform both the voltage and frequency stability can be assessed.

1) *Scenario 1:* The network is islanded at $t = 0.15s$ and the BESS switch to grid-supporting operation at $t = 0.21s$. With the proposed load models the undervoltage protection reduces the output of PV1 between $t = 0.12s$ and $t = 1s$, and switches off PV2 at $t = 0.32s$ strongly reducing the generation capacity. During grid-supporting operation the BESS are very highly loaded reducing the DC voltage and causing voltage oscillations. With constant impedance load models the voltage during the grid-feeding islanding phase is higher, therefore both PV1

Fig. 15: Modified Cigre European LV residential network. B1,B2:Battery energy storage systems; PV1:single phase photovoltaic DERs (one per phase), PV2 three phase photovoltaic DER.

TABLE IV: Exponential load model voltage-dependence factors for each load device.

Factor	CFL	LEDL	SMPS	VFD
a	1.18	1.66	-0.11	-0.09
b	0.86	2.25	2.20	2.00

and PV2 recover after the fault and the voltage recovers to nominal. The exponential load models overestimate the load after islanding since there is no load drop-off, resulting in a very low voltage.

2) *Scenario 2*: The network is islanded at $t = 0.2s$ and the BESS switch to grid-supporting operation at $t = 0.51s$. With the proposed load models the undervoltage, underfrequency and voltage change rate protection reduces the output of PV1 and PV2 between $t = 0.12s$ and $t = 0.52s$. After switching to islanded operation the PLLs attempt to track the DC-link voltage of the load, reducing the frequency and finally causing a DC voltage in the network between $t = 0.43s$ and $t = 0.51s$. After switching to grid-supporting operation the voltage recovers to nominal. With constant impedance load the voltage decreases during the grid-feeding islanding phase and recovers to nominal after switching to grid-supporting operation. The exponential load models show severe undervoltage up to $t = 0.38s$ followed by overvoltage which is caused by the effective load change when the voltage increases.

V. DISCUSSION

The results of section III indicate that the proposed models accurately represent the current transient waveform, load drop-off and DERs anti-islanding behavior of the tested physical devices. The most significant differences were found in the SMPS model during voltage dips to 0.3pu or lower. During the experiments the DC load is provided by a resistor. However, practical SMPS load devices will drop-off in this case as described by [25] which negates the error in the SMPS model.

The IEEE 2030.7 standard describes the use of static load models to assess stability during and after islanding transitions [31]. However, the case study results show significant differences between dynamics during the grid-feeding and grid-supporting islanding phases with constant impedance, exponential and the proposed load models. Constant impedance and exponential load models incorrectly model the interactions between PLLs and PRPELs during grid-feeding islanding, the amount of load during islanding due to drop-off and the inrush transients of load in the network during grid-supporting

TABLE V: Aggregated exponential load model voltage-dependence factors for each node.

Factor	Node 1	Node 6	Node 7	Node 8	Node 9	Node 10
a	0.30	1.32	0.60	1.44	0.36	0.21
b	1.84	1.47	2.04	1.91	2.13	2.04

TABLE VI: Load device apparent power per node in cases with constant impedance, exponential and proposed load models. CZ: constant impedance load, EXP: exponential load.

Node	CZ CZ (kVA)	EXP EXP (kVA)	Proposed VFD (kVA)	CFL CFL (kVA)	LEDL LEDL (kVA)	SMPS SMPS (kVA)	CZ CZ (kVA)
1	77.5	77.5	50	15	10	0	2.5
6	27.5	27.5	0	20	5	0	2.5
7	36.25	36.25	0	5	5	20	6.25
8	22.5	22.5	0	10	10	0	2.5
9	56.25	56.25	30	5	20	0	1.25
10	60	60	0	10	10	40	0

islanding. The proposed models show three main differences in dynamics. First, the rectifier and DC-link capacitor can cause a DC network voltage to occur during the grid-feeding islanding phase. Second, load drop-off changes the power balance in the network during the grid-supporting islanding phase. Third, the current inrush after switching to grid-supporting mode delays the voltage recovery for some time. When assessing FII microgrids with time-domain simulations the proposed models should be used. When using conventional load models, instability may be overlooked or falsely result from the simulations.

Although component-based models allow accurate dynamic simulations, this type of models has disadvantages which should be treated in future research. To create accurate component-based models a relatively high level of knowledge about the load devices in the network is required. In microgrids with a predefined structure such as a industrial area, hospital or university campus this information is likely to be available, however in public distribution networks the load types should be identified. As shown in section III, the current waveform of each type of load device is different which makes it suitable for harmonic load identification. Since current measurements of each individual load device is infeasible, harmonic interactions must be considered. A suitable methodology to identify load devices based on aggregated measurements is described by [32] which decomposes the measured signal in the frequency domain and identifies the different load devices based on frequency components. A load identification methodology proposed by [33] uses smart meter data to create a library of eigenloads which characterize different types of loads. The loads are identified by comparing the eigenloads of households to the eigenloads in the library. Using component-based models also increases the computational time due to the complexity of the models, which may be mitigated by aggregation of loads and DERs.

VI. CONCLUSION

This paper proposes component-based power electronic load and DERs models which enable accurate time-domain simulations of microgrid FII simulations. The models are validated by performing experiments of large voltage and frequency

Fig. 16: Comparison of phase a voltage at node 6 during FII scenario 1 with constant impedance, exponential and proposed load models.

Fig. 17: Comparison of phase a voltage at node 6 during FII scenario 2 with constant impedance, exponential and proposed load models.

transients on individual and multiple load and DER devices. A case study of a representative LV network indicates that the component-based load models should be used to evaluate the voltage and frequency stability in the microgrid, especially during the grid-feeding and grid-supporting islanding phases.

Challenges for future research consist of reducing the computation time of simulations with component-based models by model aggregation and load identification in distribution networks.

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