Hybrid Modeling of Cyber-Physical Distribution Grids

Hassani, Sina; Bendtsen, Jan Dimon; Olsen, Rasmus Løvenstein

Published in:
2021 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)

DOI (link to publication from Publisher):
10.1109/SmartGridComm51999.2021.9632321

Publication date:
2021

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Hassani, S., Bendtsen, J. D., & Olsen, R. L. (2021). Hybrid Modeling of Cyber-Physical Distribution Grids. In *2021 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)* (pp. 220-226). IEEE. https://doi.org/10.1109/SmartGridComm51999.2021.9632321

Hybrid Modeling of Cyber-Physical Distribution Grids

Sina Hassani
Wireless Communication Networks
Department of Electronic Systems
Aalborg University
Aalborg, Denmark
Email: sinah@es.aau.dk

Jan Dimon Bendtsen
Automation & Control
Department of Electronic Systems
Aalborg University
Aalborg, Denmark
Email: dimon@es.aau.dk

Rasmus Løvenstein Olsen
Wireless Communication Networks
Department of Electronic Systems
Aalborg University
Aalborg, Denmark
Email: rlo@es.aau.dk

***Abstract*—Penetration of distributed generation into distribution grids brings new demands for both centralized and distributed control at the low-voltage level. In particular, when trying to coordinate the production from distributed generation, communication becomes an important aspect of control design. However, whereas local control typically occurs at sub-second resolution, communication between geographically separate locations based on e.g., smart meter data, commonly takes place at much lower frequencies, such as on an hourly basis or even slower. Therefore, novel distribution grids should be analyzed and controlled within the context of cyber-physical systems. Hybrid systems, which cover systems that have both continuous and discrete dynamics, provide the natural setting for such analysis. In this paper, a hybrid model of the distribution grid considering both the continuous states of the power network and the discrete nature of the communication is presented, capturing the different update rates of centralized and local controllers in the modeling process. Simulation results show good agreement with data from a real-life system.**

I. INTRODUCTION

With the growing utilization of renewable energy sources, distributed generation (DG) is becoming a challenging topic in power networks. Nowadays, wind turbines (WT) and photovoltaic panels (PV) have a key role in power networks. These renewable energy sources may be found at all levels of the power network, including the low-voltage distribution grids. Despite their obvious advantages, they cause some important problems as well.

The stochastic nature of these resources is one of the problems, causing grid management in the presence of these resources to be quite hard. For instance, DG units may cause reverse power flow situations disrupting the intended operation of substations etc. Therefore, controlling the output power and consequently the voltage of the grid gain importance.

According to the past literature, voltage control structures of the distribution grids can be divided into three main categories [1]. Local, centralized, and distributed control structures are widely used in the literature, and example of these structures and methods can be seen in [2]–[6]. There are also some combined structures that gain importance recently, e.g. combined local and centralized control [7]. Since the combined approaches have advantages from both categories, they gain importance in the recent literature.

These approaches can be categorized in another way. Communication-based approaches and local measurement-based approaches can cover the control approaches. It can be seen that the centralized and distributed approaches need communication to operate. On the other side, local controllers use local measurement data to operate and generate references. Therefore, communication tools and protocols affect the centralized and distributed control structures.

Communication tools and protocols have a major role in control structures. Also, communications cause some problems in the grid. Communication delay and cyber attacks are two main problems that arise due to communications. Therefore, communications should be included in the system analysis and controller design.

Including communications in distribution grids will yield a new cyber-physical distribution grid. Cyber-physical systems are the intersection of the physical systems and cyber systems. Cyber-physical distribution grid aims at the problem of using communications as the cyber part of the system and power network as the physical part [8]–[10].

In order to see the communications effect on the distribution grid and vice versa, the system should be analyzed and controlled in a cyber-physical framework. Therefore, one of the steps is modeling the cyber-physical system such that the model includes both power grid dynamics and communication features.

There are many tools to model, analyze, and control the cyber-physical systems. Among them, the hybrid systems approach is a strong tool that can overcome this challenge. Hybrid system augment continuous and discrete features of systems in a single framework. Therefore, hybrid system can be used to model the cyber-physical distribution grid, which includes both continuous parts (power network) and discrete parts (communication network) [11].

In real-world distribution grids, smart meters and communications send the sensed data to the central controllers every 15 minutes while the local controller and power grid operate continuously. The update rate of central controller output makes some problems. Up to now, this problem is not considered in modeling and controling problems.

In this paper, a cyber-physical model is presented to com-

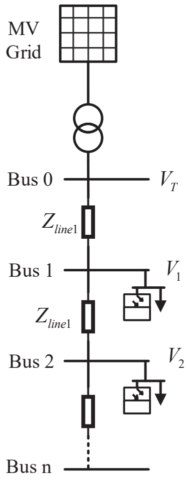

Fig. 1. A Distribution Grid Schematic.

bine the communication features and distribution grid dynamics. A hybrid model is presented which comes up with the differences in cyber and physical parts of the system and combines them in a framework. The results show the effectiveness of the modeling and reveal a difficulty that can be flattened using the presented model.

The rest of the paper is as follows. Section II present a summary of traditional model of the distribution grids. The hybrid model is presented and discussed in section III. Section IV define two scenarios and discuss the results. In section V, a discussion of the possible and useful solutions for the time delay and packet loss problems, and solution for the co-simulation problem using the presented model is discussed, and finally, section VI concludes the paper.

II. TRADITIONAL MODELING OF DISTRIBUTION GRIDS

Consider the distribution grid depicted in Fig. 1 with n buses. The distribution grid presents a low voltage distribution grid connected to a medium voltage grid through a transformer. Z_{line1} and Z_{line2} are the impedance of the first and second line, respectively. The penetration of the photovoltaic panels can be seen from the schematic.

Load flow equations of the distribution grid between bus i and bus j, are the two following nonlinear equations.

$$P_i = |V_i| \sum_{j=1}^{n} |V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{1}$$

$$Q_i = -|V_i| \sum_{j=1}^{n} |V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j), \tag{2}$$

which P, Q, V, θ, δ, and Y are the active power, reactive power, voltage, impedance angle, voltage angle, and line admittance, respectively. Based on Newton-Raphson power flow and from the above nonlinear equations, the following equation holds:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix}, \tag{3}$$

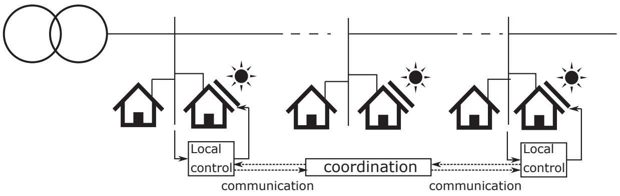

Fig. 2. Coordination Control of the Low Voltage Distribution Grids.

in which $J = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}$ is the Jacobian matrix of the load flow equations. The voltage variation is given by

$$\Delta V = K_{VP}\Delta P + K_{VQ}\Delta Q, \tag{4}$$

which K_{VP} and K_{VQ} are voltage sensitivity matrices given by

$$\begin{aligned} K_{VP} &= (J_2 - J_1 J_3^{-1} J_4)^{-1} \\ K_{VQ} &= -(J_2 - J_1 J_3^{-1} J_4)^{-1} J_1 J_3^{-1}. \end{aligned}$$

Assuming a fixed sampling rate, a discrete-time model of the distribution grid of the form

$$\begin{bmatrix} V_1(k+1) \\ V_2(k+1) \\ \vdots \\ V_n(k+1) \end{bmatrix} = \begin{bmatrix} V_1(k) \\ V_2(k) \\ \vdots \\ V_n(k) \end{bmatrix} + K_{VP}\Delta P(k) + K_{VQ}\Delta Q(k). \tag{5}$$

is formulated, where n is the number of buses in the model and k is the sampling index. Furthermore,

$$\Delta Q = \Delta Q_{PV} + \Delta Q_r, \tag{6}$$

where ΔQ_r represents changes in reactive power by other sources and loads, and ΔQ_{PV} is the reactive power of the controllable PV units. The above equation can be written on the general discrete-time state-space form:

$$x(k+1) = Ax(k) + B_u u(k) + B_w w(k), \tag{7}$$

in which $A \in \mathbb{R}^{n\times n}, B_u \in \mathbb{R}^{n\times m}$ and $B_w \in \mathbb{R}^{n\times n}$ are constant matrices, $u(k) = \Delta Q_{PV}$ is the m-dimensional control input and $w(k)$ represents disturbances and measurement noise.

As stated earlier, this modeling approach is widely used for analyzing and controlling purposes of the distribution grids. Penetration of distributed generation into the distribution grids and the problem of controlling these resources make the problem much harder to solve. In fact, centralized and distributed control methods have been proposed to control these resources in coordination [1], [12]. Fig. 2 shows the local and coordination control structure of a distribution grid. These control techniques use smart meters and communications to transfer the sensed data to the controller and from the controller to the distributed generators.

However, using this structure causes some problems from the control point of view. In fact, the local controllers change

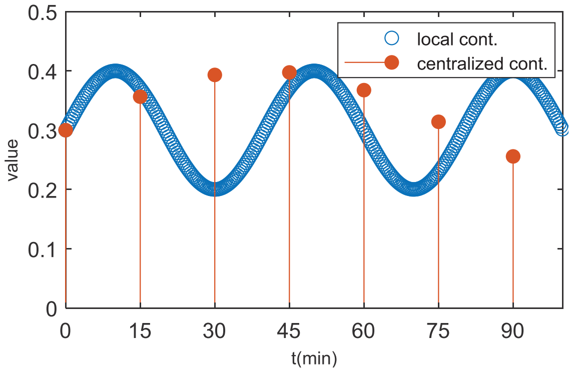

Fig. 3. Comparison of local and centralized controller update rates. Sinusoidal signals are used for illustration pusrposes.

continuously in the system structure, and they update their control command at fast sampling rates. They are also only able to sense voltage at their own connection points. On the other hand, centralized controllers need more time to receive the sensed data and send the control command back to the local controller. In practice, this period is at least about 15 minutes. Fig. 3 depicts a comparison between local and centralized controller update rates. It illustrates how the local controller update rate is very small and close to being continuous, while the centralized controller only sends data to the local controllers and PV units every 15 minutes. This considerable difference in sampling rates poses a significant challenge in terms of numerical system analysis and controller synthesis.

In short, smart meters distributed throughout the grid sense the grid voltage for about 15 minutes and calculate the mean value of their measurement data. Then, they send the aggregated data to the centralized controller. After calculating the next control command, the centralized controller sends the command to the local controllers via a communication network. The control command remains constant until the next data package arrives in the centralized controller and the controller calculates and sends out new control commands.

From a simulation and control perspective, it is clearly important to consider this difference in time scales explicitly. *Hybrid systems* represent a powerful tool to overcome this challenge. In the next section, a hybrid model of a distribution grid is presented.

III. HYBRID MODELING OF THE DISTRIBUTION GRIDS

Hybrid systems is a formalism for modeling, analysing, and performing controller design of systems that comprise both continuous and discrete dynamics. A simple example of a hybrid system is a bouncing ball falling from a height and bouncing off the ground. The speed of the ball during free fall is continuous and increasing in the downwards direction. On the other hand, when the ball heats the ground, the velocity magnitude and direction change abruptly; in other words, a jump occurs in the speed state. Traditional continuous and discrete modeling methods are not suited to model this system. Consequently, hybrid modeling methods were proposed to solve this challenge [11], [13], [14].

A general (autonomous) hybrid system model follows the scheme

$$\begin{cases} \dot{x} = f(x) & x \in \mathcal{C} \\ x^+ = g(x) & x \in \mathcal{D} \end{cases}, \tag{8}$$

where x is the state vector of the system, $\mathcal{C}$ and $\mathcal{D}$ are the so-called *flow set* and *jump set*, respectively, and f and g are the *flow map* and *jump map*, respectively. This is to be understood in the following way: as long as the states of the system are contained in the set C, the system is in the *flow condition* (a.k.a. in the continuous dynamic mode), and the values of the states change continuously according to the flow map $f(x)$. However, as soon as the system state enters $\mathcal{D}$, x immediately changes in a discrete manner (jumps) according to the jump map $g(x)$. It is worth mentioning that $\mathcal{C}$ and $\mathcal{D}$ can overlap and based on the system dynamics the jump will occur or the flow will continue in the overlap area.

As discussed in the previous section, distribution grids with data collection via smart meters and controlled by a centralized controller can also be categorized as a hybrid system, since the different components work at such different sampling time scales. In the following, a hybrid model for the distribution grid will be presented.

In accordance with the definition of hybrid systems, the system contains both continuous and discrete states. In this case, the states of the power grid change continuously, but the model of the distribution grid is discrete according to the equation (5). In order to use the hybrid system notation for the distribution grid, it is necessary to convert the system states back into continuous time:

$$\dot{V} = AV + B \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}. \tag{9}$$

It is worth mentioning that the conversion process will yield the same result if the conversion sample time and the solving sample time are equal. Solving sample time is the sampling time that the software uses for integrating the continuous-time system equations using existing solvers. Fig. 4 depicts how the simulated responses of the continuous and discrete versions to a step input is almost identical, meaning that converting from discrete to continuous time does not affect the dynamics of the system noticeably. It is thus reasonable to assume that the local controller and system dynamics are continuous. Also, it is worth mentioning that the discrete results in Fig. 4, is the result of the solving the distribution grid using Newton-Raphson flow analysis.

The centralized voltage controller of the distribution grid sends the control command periodically. Therefore, a timer is defined for the modeling process such that the timer counts until it reaches a specified value. During this time, the local controller and the system uses the previous control command. When the timer reaches the specified value, it will reset to zero. In other words, a jump occur in the timer state. On the other hand, the centralized controller updates its value or it can be stated that a jump occur in the control command.

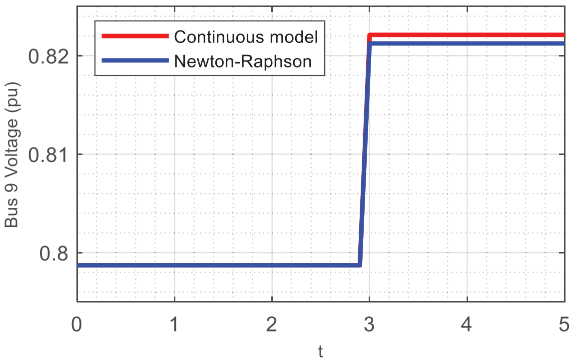

Fig. 4. Comparison between continuous model and the Newton-Raphson solver-based equations.

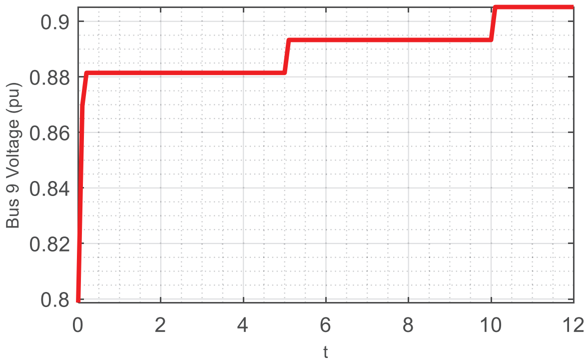

Fig. 5. Bus 9 voltage profile in the presence of local and central controller.

Therefore, the states of the hybrid distribution grid can be written as follows:

$$x = \begin{bmatrix} V \\ u \\ \tau \end{bmatrix}, \tag{10}$$

which V, u, and τ are the voltages of the buses, control command of the centralized controller, and timer of the communication.

The flow map and the flow set of the hybrid distribution grid can be written as follows:

$$\dot{x} = f(x) = \begin{bmatrix} AV + B \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \\ 0 \\ 1 \end{bmatrix} \qquad \tau \in [0\ ,\ T] \tag{11}$$

It can be seen that during the time interval $[0\ ,\ T]$, the voltage states change their values according to the continuous equations, the centralized controller command remains constant, and the timer state τ starts from zero and grows at a constant rate. When the timer state reaches T, a jump occurs and the timer will be reset to zero, and the central control command updates its value according to the sensed data. Therefore, the system will proceed according to the following jump map:

$$x^+ = g(x) = \begin{bmatrix} V \\ \kappa(V) \\ 0 \end{bmatrix} \qquad \tau \in \{T\}. \tag{12}$$

The above equation states that during the jump (when $\tau = T$), the voltages remain constant at the value they have reached at time T, the centralized control command is updated, and the timer is reset to zero.

As can be seen, the hybrid model of the distribution grid (11)–(12) follows the formalism presented in (8) with $\mathcal{C} = \mathbb{R}^n \times \mathbb{R}^m \times [0\ ,\ T]$ and $\mathcal{D} = \mathbb{R}^n \times \mathbb{R}^m \times \{0\}$.

IV. SIMULATION RESULTS

In the following, two scenarios are defined to show the importance of the presented model. The first scenario shows how the centralized controller sends the control command, and how the model works during flow set and jump set. The second scenario shows the importance of hybrid modeling of distribution grid.

The hybrid distribution grid is simulated in the Hybrid equations (HyEQ) toolbox [15] in MATLAB.

The case study is a low-voltage distribution grid belong to Thy-Mors Energi in Denmark [16], first presented in [7]. In this grid, a PV unit is connected to bus number 9. The reactive output power of the PV unit is controlled using both local and centralized control. As mentioned earlier, the centralized controller would update the control law every 15 minutes in practice, but 5-second update intervals are considered here for the sake of illustration.

A. Hybrid distribution grid modeling

In this scenario, the controlled PV unit will join the distribution grid at the beginning of the simulation. The local controller control the output reactive power immediately. Fig. 5 presents the voltage profile of the distribution grid. It can be seen that the PV and local controller change the voltage value at the beginning of the simulation. Later at $t = 5$, central controller change its value and remain constant for the next 5 seconds. it can be seen that the voltage goes up in this moment, and it will remain constant until the next control command arrives. Consequently, at $t = 10$ the central controller changes its output. This process will continue for the next 5 seconds of the simulation.

The central control law simulated in this paper is the following simple integral controller with deadband:

$$u^+ = \begin{cases} u + \alpha & V_i \leq 0.9 \\ u - \alpha & V_i \geq 1.1 \end{cases}, \tag{13}$$

in which α is a constant amount of reactive power, and V_i is the voltage of the controlled bus. Note further that k in (13) is the discrete sample index of the centralized controller, not the local control.

Fig. 6 depicts the timer state profile during the simulation. It can be seen that the timer starts from zero and goes up continuously during the flow set. At the jump set ($\tau = 5$), this state changes its value to zero or in other word, a jump occur in the system. The timer again starts to count from zero, and the process will be continued.

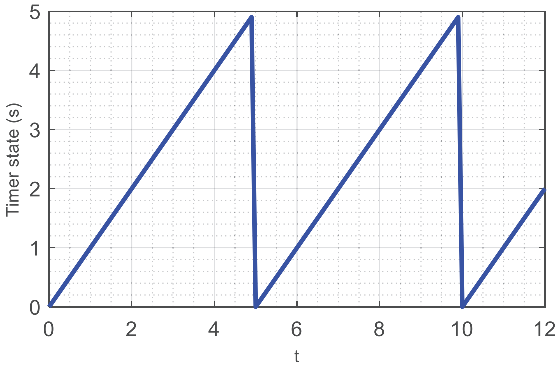

Fig. 6. Timer state of the hybrid model.

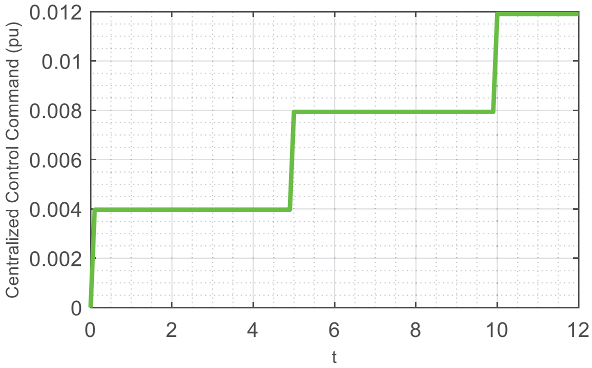

Fig. 7. Central control law state of the hybrid model.

Same process is true for the control command. Fig. 7 shows the central control command of the distribution grid. It can be seen that the control command is constant during the flows, and at the jumps, it changes value. The jump in the central control command is the cause of the jump in the voltage states of the distribution grid.

The local controller in this scenario is a $Q-V$ control structure, and the centralized controller shifts the $Q-V$ curve up and down according to the situation. In other words, the centralized controller yields a reference for the local controller.

B. Effect of disturbances in the middle of updating rate of centralized controller

In this scenario, the effects of disturbances are investigated on the distribution grids. In this scenario, a load increase occurs at $t=2$; therefore, the voltage of the buses decreases accordingly. Fig. 8 shows the voltage profile of bus 9. It can be seen that the local controller cannot compensate for this voltage decrease; therefore, central controller should try to compensate for the deficit. Since the centralized controller only updates its command signal every five seconds, the system must wait until $t=T=5$. At this time, the centralized controller updates its value properly and compensates the voltage.

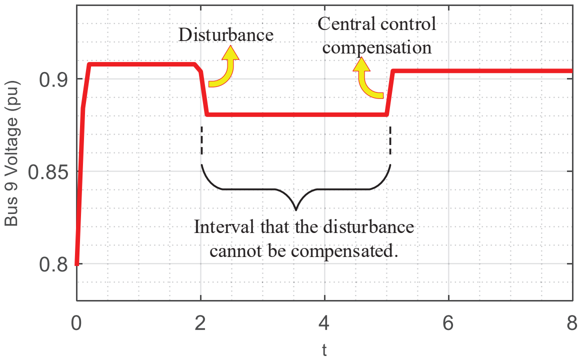

Fig. 8. Voltage profile of bus number 9 in the presence of load change.

The important message of this scenario is that the central controller cannot compensate for quick disturbances and faults of the grid, since it updates slowly compared to the grid dynamics (every 5 seconds in the simulation presented here, but there will likely be at least 15 minutes between command updates in real-world scenarios, as explained in [7]).

It can be seen that this modeling of the distribution grid includes the latency of the central controller. Therefore, in order to control and analyze the system using this model will be more accurate and correct. On the other hand, using the traditional model for designing the centralized controller will result in incomplete analysis and design models and the real-world results may be far from the expected results.

V. DISCUSSION

In this section, a short discussion of the problems and solutions that can be presented using the proposed model is discussed. Therefore, in the following two subsections, two main problems that arise from communications are discussed and appropriate solutions for them are stated. Later, the necessity of the presented model and the effect of the model on the analysis and design of the solutions are discussed. In the third subsection, a short discussion on the co-simulation is presented.

Time delay and packet loss are the most common problems when relying on communication systems, and in particular at the transport layer. Delays and packet losses happens at layers 1-3, and is handled differently with UDP and TCP and therefore shows different characteristics in response to delays and packet losses. There may be many different causes for delays and packet losses, e.g. noise at signal levels and surrounding, other communicating units creating disturbances, high network loads, various types of network faults and cyber attacks. Therefore, a model-based approach to deal with these problems will be useful and in the following, a short description of the possible solutions will be discussed.

A. Time Delay

Delay is a concern for both UDP and TCP and depending application layer protocols. Time delay can be caused by low data rate technology, wrong or poorly configured hardware, congested networks and loaded routers or even source or end points may turn out to be bottlenecks. According to [17], time delay can be from milliseconds to several minutes. The impact of time delays on the distribution grids are investigated in [18]. In this investigation analysis is done using simulations and hardware-in-the-loop methods, but it lacks a model- and theory-based analysis for fully understanding impact of delay at transport layer level.

According to the last paragraph, there is still room for a model-based analysis delay impact on the distribution grids. The advantageous of the model-based analysis can be stability, passivity, and proof-based analysis and design which considers non-ideal communication networks. Hence, control methods and solutions will be more reliable to the real world.

The model presented in this paper can be extended to encompass time delays. Hence, methods and solutions to different delay times can be presented by the researchers based on this model, and stability and passivity analysis in the presence of delays can also be investigated. Due to space concern it is not applicable to present the extended model in this paper.

B. Packet Drop

Packet drop or packet loss is another concern in communications, caused by e.g. noise in data packets at physical layer, overloaded routers or (un)intentional tampering with data packets. For UDP based protocols packet losses leads directly to a loss of message (control or measurement update), while TCP, if connectivity is otherwise reasonable, leads to retransmission and prolonged delays, and may be treated by special stochastic delays, see e.g. [19].

Due to the stochastic nature, packet drops cannot be predicted, but may easily be correlated posing a challenge that once it happens, it would often reoccur. Therefore, methods to make solutions robust against packet drops is important.

Robust techniques can be presented in order to solve this problem.

The model presented in this paper is able to analyze the problem correctly since if a packet lost in the communication, the model considers the time delay and update rate correctly. In the low voltage distribution grid case, if a packet lost, the system should wait for the next 15 minutes in order to receive an updated centralized control signal.

According to the last paragraph, analyzing the system stability and passivity, and designing controller for the system using the presented method will be accurate and beneficial.

C. Co-simulation

In the cyber-physical systems, the co-simulation of the cyber and physical systems is a problem and addressed in the literature [20]–[23]. Since there is not any model compromise both cyber and physical parts of the system, the co-simulation and synchronizing the two models are always a challenge. Therefore, presenting a model which comprise the cyber and physical parts will solve the problem. The model presented in this paper compromise the communication and power system model; therefore, it solves the co-simulation problem, and there is no need for co-simulation and synchronizing the cyber-physical systems components.

VI. CONCLUSION

In this paper, a hybrid model is presented for the distribution grid considering communication features of a centralized controller. The model includes both the communication properties and distribution grid dynamics; therefore, the model is a cyber-physical model. The fact that the centralized controller proposed in this paper, updates the control law in long periods of time is modeled and investigated. The results show that the model truly represents the cyber and physical parts of the system. Also, results show that using this model for analyzing and controlling the system is more accurate and closer to real-life system compared to previous discrete time models, and it will help to design more accurately and practically. Finally, using cyber-physical models can be the start of combining communications and power grids in order to have better analysis and control on the system. Also, this paper starts to present a cyber-physical model to have a better representation of the system, and as the next steps, solutions to time delays and packet loss will be presented based on this model.

REFERENCES

[1] K. E. Antoniadou-Plytaria, I. N. Kouveliotis-Lysikatos, P. S. Georgilakis, and N. D. Hatziargyriou, “Distributed and decentralized voltage control of smart distribution networks: Models, methods, and future research,” *IEEE Transactions on smart grid*, vol. 8, no. 6, pp. 2999–3008, 2017.

[2] E. Demirok, P. C. Gonzalez, K. H. Frederiksen, D. Sera, P. Rodriguez, and R. Teodorescu, “Local reactive power control methods for overvoltage prevention of distributed solar inverters in low-voltage grids,” *IEEE Journal of Photovoltaics*, vol. 1, no. 2, pp. 174–182, 2011.

[3] M. S. Chong, D. Umsonst, and H. Sandberg, “Local voltage control of an inverter-based power distribution network with a class of slope-restricted droop controllers,” *IFAC-PapersOnLine*, vol. 52, no. 20, pp. 163–168, 2019.

[4] L. Wang, D. H. Liang, A. F. Crossland, P. C. Taylor, D. Jones, and N. S. Wade, “Coordination of multiple energy storage units in a low-voltage distribution network,” *IEEE Transactions on Smart Grid*, vol. 6, no. 6, pp. 2906–2918, 2015.

[5] S. Bolognani, R. Carli, G. Cavraro, and S. Zampieri, “Distributed reactive power feedback control for voltage regulation and loss minimization,” *IEEE Transactions on Automatic Control*, vol. 60, no. 4, pp. 966–981, 2014.

[6] Y. Wang, M. H. Syed, E. Guillo-Sansano, Y. Xu, and G. M. Burt, “Inverter-based voltage control of distribution networks: A three-level coordinated method and power hardware-in-the-loop validation,” *IEEE Transactions on Sustainable Energy*, vol. 11, no. 4, pp. 2380–2391, 2019.

[7] Y. Gui, J. D. Bendtsen, and J. Stoustrup, “Coordinated control of pv inverters in distribution grid using local and centralized control,” in *IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society*. IEEE, 2020, pp. 1773–1778.

[8] X. Yu and Y. Xue, “Smart grids: A cyber–physical systems perspective,” *Proceedings of the IEEE*, vol. 104, no. 5, pp. 1058–1070, 2016.

[9] E. Drayer, J. Hegemann, S. Gehler, and M. Braun, “Resilient distribution grids—cyber threat scenarios and test environment,” in *2016 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*. IEEE, 2016, pp. 1–6.

[10] M. Findrik, P. Smith, J. H. Kazmi, M. Faschang, and F. Kupzog, “Towards secure and resilient networked power distribution grids: Process and tool adoption,” in *2016 IEEE International Conference on Smart Grid Communications (SmartGridComm)*. IEEE, 2016, pp. 435–440.

[11] R. Goebel, R. G. Sanfelice, and A. R. Teel, “Hybrid dynamical systems,” *IEEE control systems magazine*, vol. 29, no. 2, pp. 28–93, 2009.

[12] M. Karimi, H. Mokhlis, K. Naidu, S. Uddin, and A. Bakar, “Photovoltaic penetration issues and impacts in distribution network–a review,” *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 594–605, 2016.

[13] M. S. Branicky, “Introduction to hybrid systems,” in *Handbook of networked and embedded control systems*. Springer, 2005, pp. 91–116.

[14] R. G. Sanfelice, *Hybrid Feedback Control*. Princeton University Press, 2020.

[15] R. Sanfelice, D. Copp, and P. Nanez, “A toolbox for simulation of hybrid systems in matlab/simulink: Hybrid equations (HyEQ) toolbox,” in *Proceedings of the 16th international conference on Hybrid systems: computation and control*, 2013, pp. 101–106.

[16] “Thy mors energi,” https://www.thymors.dk/.

[17] K. Shahid, L. Petersen, F. Iov, and R. L. Olsen, “On the impact of using public network communication infrastructure for voltage control coordination in smart grid scenario,” in *Smart grid inspired future technologies*. Springer, 2017, pp. 3–14.

[18] K. Shahid, E. Kidmose, R. L. Olsen, L. Petersen, and F. Iov, “On the impact of cyberattacks on voltage control coordination by regen plants in smart grids,” in *2017 IEEE International Conference on Smart Grid Communications (SmartGridComm)*. IEEE, 2017, pp. 480–485.

[19] K. Shahid, A. Saeed, T. le Fevre Kristensen, and R. L. Olsen, “Impact of transport layer protocols on reliable information access in smart grids,” in *2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*. IEEE, 2017, pp. 1–6.

[20] S. Chatzivasileiadis, M. Bonvini, J. Matanza, R. Yin, T. S. Nouidui, E. C. Kara, R. Parmar, D. Lorenzetti, M. Wetter, and S. Kiliccote, “Cyber–physical modeling of distributed resources for distribution system operations,” *Proceedings of the IEEE*, vol. 104, no. 4, pp. 789–806, 2016.

[21] C. I. Ciontea, K. Shahid, F. Iov, and R. L. Olsen, “Flexible platform for the study and testing of smart energy systems enabling-technologies,” in *2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*. IEEE, 2020, pp. 1114–1119.

[22] H. Lin, S. S. Veda, S. S. Shukla, L. Mili, and J. Thorp, “Geco: Global event-driven co-simulation framework for interconnected power system and communication network,” *IEEE Transactions on Smart Grid*, vol. 3, no. 3, pp. 1444–1456, 2012.

[23] S. C. Müller, H. Georg, J. J. Nutaro, E. Widl, Y. Deng, P. Palensky, M. U. Awais, M. Chenine, M. Küch, M. Stifter *et al.*, “Interfacing power system and ict simulators: Challenges, state-of-the-art, and case studies,” *IEEE Transactions on Smart Grid*, vol. 9, no. 1, pp. 14–24, 2016.