Using clock accuracy to guide model synthesis in distributed systems: An application in power grid control

D. M. Anand, J. G. Fletcher, Y. Li–Baboud, J. Amelot and J. Moyne

***Abstract*—Practical implementations in distributed model based control face a fundamental trade-off between model complexity and the number of modeled nodes. For linear systems, higher order models better capture the behavior of the system at higher frequencies, but the effective operating frequency range is limited during implementation due to sensor/actuator bandwidth limits, control algorithm limits and, in the case of wide scale distribution, communication bandwidth limits. The optimal choice for model order is the intersection of increasing model fidelity and the increasing generalized cost. Using existing methods for optimal model synthesis we present an evaluation of this cost in terms of clock synchronization accuracy. We show through illustrative example in the domain of large scale power transmission that there is a growing performance penalty as model order is increased in the presence of uncertain time-stamps. We discuss how this penalty can be framed as a design parameter for automated model deduction. As a corollary, we also show that the choice of a network based clock synchronization method can be formalized by using the same performance metric used for model synthesis.**

Keywords: time synchronization, networked control, model order deduction, data quality, PTP, NTP, power systems control

I. INTRODUCTION

In this paper we present recent advances in transmission and distribution of electrical power. We refer to the collective system of current carrying conductors, sensors, swtiches/actuators and the hierarchy of control and data management as the "power grid" or the "energy grid". The energy grid is an interesting control problem in part because it is spatially distributed over a very wide area (hundreds of kilometers). Control for this wide area is often decentralized and redundant for fault tolerance. Control methods for this system are designed with these considerations in mind. An essential enabler for these control concepts is the availability of high quality data from all sensing and collaborating control components. Data quality is an aggregate term for several properties. The property in focus here is the precision and accuracy of time-stamps applied to the data; a function, in turn, of the clock accuracy at each node. We propose that since the data quality is heavily dependent on distributed clock synchronization [1], we need to factor nodal clock performance into the development of mathematical models and the design of the control logic. We include nodal clock uncertainty as a penalizing cost to limit the frequency range over which a mathematical model should be considered valid. The motivation being that an overly complex model uses additional resources to simulate data over frequencies where 'noise' introduced due to timing uncertainty would offset any gains from added model complexity.

While this paper does deal almost exclusively with the energy grid as the use case, the concepts of weighing clock accuracy, synchronization tolerance and communication constraints against model fidelity, and sampling rate are generally applicable to a wide array of problems in distributed, networked and co-operative control arrangements. The paper is structured as follows. Section II discusses the energy grid in more detail. Section III discusses the model deduction algorithm we use and introduces the model of the transmission line. Section IV presents applications of network clock synchronization in the energy grid and then discusses a scheme where time-stamp inaccuracy is factored into the deduction algorithm. Finally, results from the illustrative example and conclusions are presented in sections V and VI.

II. MODELING AND CONTROL IN THE ENERGY GRID

As sensor performance and computing power advance, new modeling and control techniques can be implemented to improve monitoring and control of distributed systems such as the energy grid. Three common energy grid control applications which illustrate the variation in timing requirements are generation scheduling, automatic generation control (AGC), and special protection schemes (SPS). Generation scheduling involves matching the available generation to the predicted load, and is generally done on a daily basis by bringing generators on or off line [2]. AGC control is implemented on a second to minute scale and is used to adjust generators in operation to keep frequency stable [3]. Both these services are satisfied by a networked SCADA (Supervisory Control and Data Acquisition) system, which polls devices at 1 to 2 second intervals. In contrast to these relatively long sampling intervals, SPS algorithms may include load shedding or line tripping operations, which may need to occur within milliseconds of a detected fault condition. For this reason, SPS control schemes are usually hard-wired and implemented locally [4].

The present and future of the energy grid is based upon critical advances in wide area monitoring and control. Advances in communication and network topologies have made it possible to aggregate information from many nodes separated by vast distances in a timely manner. Improvements in computational power and speed have increased the amount of computation that can be executed by each node in the system. The convergence of these two factors means that a distributed system such as the energy grid can be controlled over a network with a response time much lower than the SCADA based system; low enough to be useful for any application, including critical safety algorithms and SPS implementations.

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A key enabler in this transition towards advanced timing requirements is the phasor measurement unit (PMU). PMUs are sensors that report data in the form of synchrophasors; time-stamped measurements of magnitude, phase, and frequency of both current and voltage waveforms. The following is a brief list of PMU specifications, more information can be found in [5] and [6]:

- The PMU is a high fidelity sensor capable of sampling voltage and current waveforms at rates up to $10,000$ Hz.
- The synchrophasor is a vector measurement which is reported at a rate of up to 60 Hz.
- These compiled reports are time-stamped, accurate to within 1 μs of coordinated universal time (UTC).
- Synchrophasors from multiple PMUs are combined based upon corresponding time stamps to provide a snapshot of grid conditions.

Mathematical modeling of the energy grid is another key research thrust, and when used in conjunction with accurate sensing and network communication is vital for improved analysis and control. An example of these components working in unison is model based estimation [7]. When components are networked and large communication delays are common, model generated estimates are used to 'smooth' the reported data or to interpolate conditions on the wire in between locations where real measurements are available. This facilitates the placement of virtual sensors where physical sensors are not present. Since the energy grid can contain a vast number of nodes, ranging from hundreds to tens of thousands depending on the application [8], it is impractical to solve full-model equations in reasonable time for online model integration. For example, it is common practice to run power flow and failure analysis simulations using a large scale, accurate model of the transmission system. These simulations provide critical information regarding system capabilities and failure performance. The full model simulations take time to run, however, and therefore do not have the performance required to be used for real time control. Instead, it is common to use a reduced model that meets the speed of simulation required for control, but also reflects enough of the characteristics of the system to be useful. Automated or assisted model order reduction/deduction is a powerful tool to reach this optimal choice for model order. The transmission line example described in the next section demonstrates a system where the starting point is a simple model but one which can be scaled up (or deduced) automatically using the deduction algorithm to increase the number of π sections modeling the system until a performance bound is reached.

III. MODEL ORDER DEDUCTION

To pose model synthesis of a power transmission line as a problem for automated modeling, we will first define the order deduction process in spirit. At a level below the logical abstraction used by the controllers to decide when switches close, change overs occur, or failsafe circuits are opened, there is a spatially distributed continuum expressed in a set of ordinary differential equations. In the case of the power system, this is a vector field of voltages and currents subject to transformations through inductances and line capacitances. A common modeling simplification for systems assembled from repeating components or sub-models is to use lumped parameter models. The electrical power transmission system, for example, can be expressed as a finite set of interconnected "capacitive, inductive and dissipative" elements. Networks of these elements can be assembled into discrete units representing nodes, switches, etc. A further simplification is to say these functional blocks are linear and the parameters are time-invariant. These assumptions are common place in electrical system modeling as seen in [9]. The authors in [10] discuss a few example cases of model reduction for non-linear circuits. The assumption of lumped linear models does not detract from the motivation or the algorithmic approach, but allows us to use the order of coupled ordinary differential equations to mathematically express "complexity".

Model order deduction is an automated approach to finding a 'proper' model. The basic strategy is to start with a simple model for a dynamic system and then to iteratively add complexities (model order in linear systems) until a stop condition is reached. Several exit conditions and details about the basic algorithm are presented in [11], [12] and [13]. For a linear model of the transmission line, states are added to the state space model in the form of generalized inductive and capacitive elements at each node and in the interconnects until a proper model order is reached.

For the system in this paper we use the frequency domain model order deduction algorithm (FD-MODA) presented in [12]. We first determine a frequency range of interest (FROI). The authors in [11] specify that the model should be accurate at frequencies 2-6 times the maximum input frequency. The maximum input frequency ω_{in} in our case is the upper limit of the envelope of frequencies input to the transmission line. For this paper we will set this at $3000Hz$ based on the work presented in [14] and on the fundamental limits of the sampling process in a PMU. The upper limit for the FROI is $\omega_{max} = (5 \times \omega_{in}) = 15KHz$. According to the FD-MODA algorithm, a proper order r is reached when the state $r+1$ does not appreciably change the frequency response, G, of the system within the FROI. As the lumped parameter models are divided into finer and finer submodels, a threshold is reached when the frequency response and continuum model of the system are close. Equation 1 shows the stop condition for the FD-MODA algorithm.

$$\delta G_n^r = \max|\frac{G^{r+1}(j\omega)}{G^r(j\omega)} - 1| < TOL_m \tag{1}$$

Where, $\omega \in FROI = [0, \omega_{max})$ and the frequency response convergence tolerance TOL_m is picked as necessary. In our case $TOL_m = 0.01$, or 1% error in the model frequency response. Further, if the model of the system is made up of m connected components with ranks $[r_1, r_2 ... r_m]$ FD-MODA increases the rank of the system model iteratively while minimizing $r = \sum r_i$, i.e. increasing the rank of the most sensitive component before the others.

IV. USE CASE

The linear system presented here is that of a power transmission line modeled as a π-model. Figure 1 shows the scalable

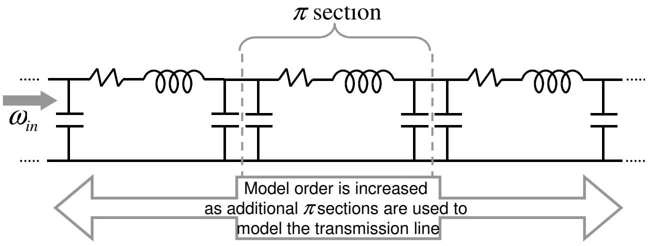

Fig. 1. Schematic representation of the π-model for a single phase power transmission line. The center section represents a single π section, and many π-sections in series model the transmission line.

π-model of the transmission line. The number of sections, (highlighted in the schematic), can be arbitrarily scaled up as mandated by the MODA algorithm. This is an ideal candidate for an example since the model properties approach continuum behavior as it is discretized into finer and finer π-sections. The system parameters (inductance, capacitance and impedance) for each π-section also change as the order is increased. We use the MATLAB SimPowerSystems simulation package to develop our models. Since we are only modeling one homogenous element, we can directly attempt to meet the condition in Equation 1 without having to run through the iteration step to find the most sensitive sub-model. If there were other components in the system such as capacitor banks, filters, loads and generators, then the general class FD-MODA algorithm discussed in [12] is still a valid approach.

An example use case highlighting the need for a MODA optimized π-model is in the estimation of the state of a feeder line between shared transmission assets where the PMUs are only available at the terminal nodes. Let us consider an application as shown in Figure 2 where a 10 kilometer long 26.5KV feeder line connects two substations both with captive spinning reserves (small generators designed to compensate for transient load fluctuations). The closed loop control of these generators is achieved through measurements from the local PMU and estimates of transmission line state and the state of the remote substation. The switching station located somewhere along the transmission line switches in the remote generator when required. This switching event sets off a transient state on the feeder line which is measured by both PMUs at the local and remote end. The standing practice to prevent a parasitic oscillation resulting from this perturbation is to estimate the effect of this event on the transmission line, which requires an accurate representation of the transient phenomenon across the transmission line. Since it is infeasible to string phase sensors over the entire length of the feeder line to build this estimate, a mathematical model of transmission line is used instead in conjunction with available sensor data to build a model-in-the-loop estimator. In such a case, the model of the transmission line becomes critical in monitoring the state of the transmission line. These models must account for the electro-magnetic properties of the transmission line and the methods for sampling the line. Since the performance of this model is subject to the same data quality and reporting constraints as the sensors in the network, clock performance begins to play a role in the model performance as well. For example, any noise (clock error) in time stamping process at the switching station would manifest as errors in the model generated estimate of the state of the remote node. Similarly, the loss of clock precision on the PMU sampler would corrupt the correlation between the real PMU measurements and the modeled signal. Ideally this information must be incorporated into the model in order to optimize the hybrid performance of the collective system.

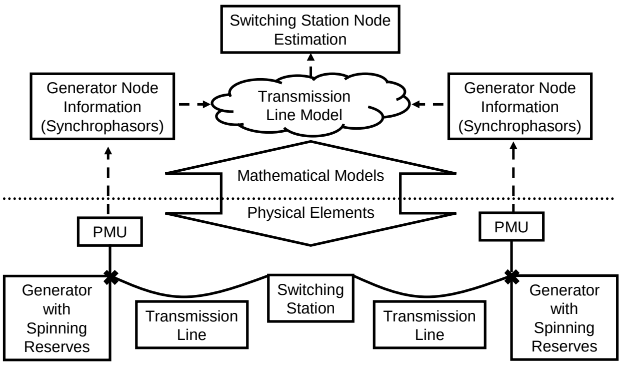

Fig. 2. Schematic representation of the coupled interaction between physical elements and mathematical elements discussed in the use case. PMUs serve as the interface between the two domains.

A. *Clocks and control in a networked system*

Clock synchronization is a fundamental consideration in the design of synchrophasor networks. The design goal is to ensure that each PMU be synchronized to within 1 μs of UTC and each synchrophasor is time-stamped with the same accuracy.

Currently, GPS clock signals are used to synchronize PMU devices as they can provide a time accuracy accurate to within a few nanoseconds [15] of UTC. As PMU devices become more common, it is more likely for a PMU to be installed in a location where GPS is not available for economical or environmental reasons. Instead, there is a lot to be gained by extending the currently existing standard for substation networking, IEC-61850 [16], to incorporate network clock synchronization techniques. The IEC-61850 standard currently covers the following aspects of substation networking:

- Common data format for exchange between substation components such as PMUs, Switches, etc.
- A fully compliant 10/100/1000 Mbps Ethernet interface.
- Wide area networking policies between substations, control centers and remote operators compatible with addressing and protocol specifications of the Internet.
- A specific format for network transmitted time-stamps.

B. *Goals for IEEE-1588 PTP in the Smart Grid*

With the pervasive use of switched IP networks for the current implementation of grid control, there is an effort to determine the capabilities of IEEE 1588 Precision Time Protocol (PTP) within energy grid networks and the clock synchronization requirements of devices on the network. PTP is a natural candidate to serve as a clock synchronization extension to IEC 61850 as it is the only current network synchronization algorithm which could potentially provide the necessary accuracy to achieve the time-stamp accuracy discussed in Section II. Performance of PTP in local area

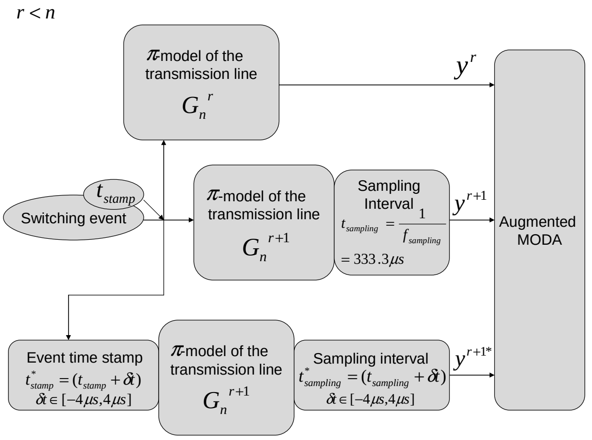

Fig. 3. Schematic representation of the decision inputs when clock accuracy is added to the MODA system. The current model order is r, such that $r < n$ where n is the maximum model order available.

networks is presented in [17] and [18] and performance evaluation of the protocol in the power grid control infrastructure is currently being conducted by IEEE-1588 Working Group 87, Power System Relaying Committee (IEEE-PSRC) and NIST. PMU devices synchronized using PTP can be installed in areas where it is difficult to install GPS antennas. They may also use one antenna to synchronize a PTP grandmaster which in turn serves several PTP clients in a local area, thereby extending GPS clock accuracy through local subnets and reducing the cost associated with the installation and maintenance of multiple GPS antennas. The need for time synchronization in substations extends to many intelligent electronic devices (IED)s beyond PMUs, such as digital fault recorders and sequence-of-events recorders, which require time-stamps accurate to a millisecond [15]. Implementation of PTP would provide synchronization of all IEDs, including PMUs, within an automated substation network with the time accuracy necessary for their basic operation.

C. Building models with timing constraints

To be able to integrate mathematical models into this new network architecture with network clock synchronization, we first need to be able to express the dynamic clock uncertainty in the network as a form of process noise in the mathematical model for the integrated system. Some strategies for introducing sampling effects and communication corruption into the modeling of distributed systems are presented in [19] and [20]. A form of frequency bounded stochastic truncation can be used to identify process uncertainty close to the sampling frequency. While this is a useful tool for controller design, we still have to understand the stochastic properties of clock error and translate that to uncertainties in the model.

Since we are using the FD-MODA algorithm for model synthesis and we are only interested in the maximum difference in the frequency response, we will attempt to treat the timing inaccuracy as a form of “noise” injected at the output of the model. Justification for this approach can be found in work done in the field of network control systems, where time delays in communication have to be formulated as process noise for control design [21]. The authors in [19] show that superposition holds true for linear systems with random time delays; we can therefore introduce a time corrupted form of the input signal to an identical system model to yield the ‘noisy’ output y_n^{r*} and then claim that $\|y_n^{r*} - y_n^r\|$ is a suitable measure of output side sensitivity to clock uncertainty. To stay true to the FD-MODA algorithm we will use frequency response over the range of interest as the sensitivity metric for $\|y_n^{r*} - y_n^r\|$. To achieve this we use the exit condition shown in Equation 2. TOL_c is the allowed tolerance for change in frequency response of the system due to inaccurate data reconstruction with given time stamp accuracy. In our case $TOL_c = 0.25\%$ or one quarter of the tolerated model error. The choice for TOL_c is a design parameter and picked in this case based on practical experiments involving model based estimation on clock synchronized controllers discussed in [22].

$$\delta G_n^{r*} = \sqrt{\sum \frac{(G^{(r+1)*}(j\omega) - G^{r+1}(j\omega))^2}{(G^{r+1}(j\omega))^2}} > TOL_c \qquad (2)$$

V. RESULTS

We use the the FD-MODA algorithm on a π-section model of a power transmission line introduced in Section IV. The π model converges to a high fidelity representation of the phase and frequency dynamics of a real life conductor carrying AC waveforms (within TOL_m). To decide on a satisfactory level for this granularity of division, we use an augmented form of the FD-MODA technique [11]. We perform the increased order sensitivity test to find if increasing the model order makes a significant contribution to the frequency response characteristics of the system. Additionally, we perform another test to check if the added model order ends up reducing the effective performance of the system because of loss in frequency response precision as the system approaches the limits of clock accuracy. This clock accuracy is a function of synchronization method used as discussed in Section IV. Figure 3 outlines our simulation approach used to introduce clock inaccuracies in the model integration process where we attribute a random delay in the interval $[-4\mu s, 4\mu s]$ to both the switching event, which excites the dynamics of the transmission line, and the sampling interval within the PMU to simulate drift in the PMU sampling clock. Details are discussed in the subsequent sub-sections.

A. Model response with changing model order

The transmission line model described in Section IV was subjected to a 265KV 60Hz AC input waveform. Figures 4-A and 4-B show the input output characteristics of the transmission line model with 20 and 90 π-sections respectively. Both plots show the response of the model to a circuit breaker ”close” event at 0.002 seconds. Figures 5-A and 5-B show the magnitude spectrum for the frequency response of the 20 and 90 π-section models respectively. As the model order is increased, the response to higher frequencies is significantly increased, which is especially visible on Figure 5 close to 100KHz. The FD-MODA algorithm was applied to the transmission line model with FROI=15 KHz in order to meet the desired tolerance TOL_m. The model order was

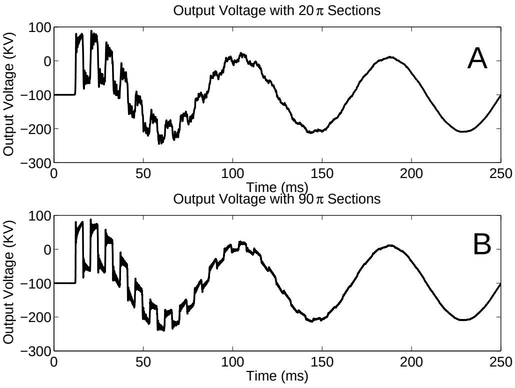

Fig. 4. 265 kV, 60 Hz transmission line voltage waveforms under circuit breaker closure condition. The output response presented in plots A and B correspond to models using 20 and 90 π-sections respectively.

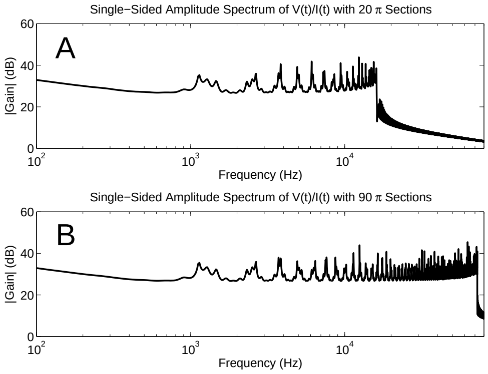

Fig. 5. Frequency response of models using 20 π-sections (Plot-A) and 90 π-sections (Plot-B). Plot-B shows that the model with 90 π-sections has a higher gain at higher frequencies.

iteratively increased by the algorithm until the error norm of the frequency response between order r and $r+1$ was less than 1%, which occurred on the addition of the 86th π-section. Figure 6 shows that there is also a significant improvement in model performance within the FROI with increasing order.

B. Model response with timing uncertainty

The simulations discussed in Section V-A do not account for the possibility of time corruption in the process of reporting and sampling data. Uncertainty in the exact time at which the switching event occurred and uncertainty in the trigger signal for the sampling process were added to the simulation. The assumption being that as the model order is increased it exhibits increased sensitivity to clock corruption. This phenomenon is confirmed in Figure 7 where we see a growing error norm with increasing model order. Intuitively, the higher order models have a larger spectral radius and therefore are more sensitive to time uncertainty. The error norm in the figure is calculated assuming a time-stamp error between the limits $[-4\mu s,...,4\mu s]$. This range was chosen based on the nominal performance of the precision time protocol (PTP) presented in [23]. The authors experimented with PTP over an undersea network connecting ocean observatories and off shore sensors spanning an area of tens of kilometers. The results in [23] show that at steady state the system offsets have a zero mean with frequent offset corrections of up to $+/-4\mu s$.

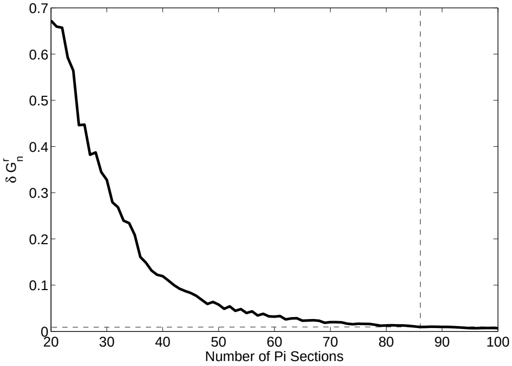

Fig. 6. Max norm of MODA algorithm applied to the transmission line model. The norm drops below a tolerance of 0.01 at 86 π-sections

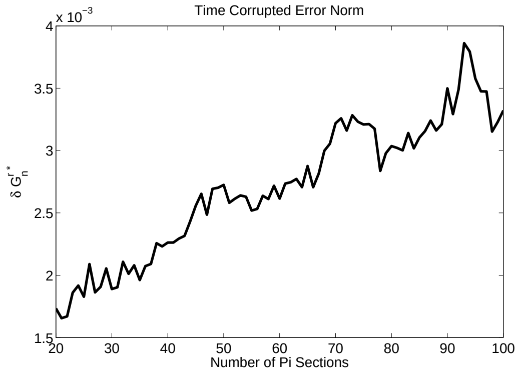

Fig. 7. Error norm with the addition of clock errors in sampling and time-stamping. The norm exceeds 0.025 at 48 π-sections.

We then invoked the FD-MODA algorithm with an additional exit condition represented by Equation 2 to ensure TOL_c is not violated. The resulting deduced model had 48 π-sections, showing that it is not possible to meet both given performance parameters TOL_m and TOL_c. The designer is now faced with the choice of either improving the timing accuracy within the network or to compromise on the desired model fidelity. In this use case, a model with 48 π-sections satisfies TOL_c but has a model error of about 1 percent, which is ten times the desired value for TOL_m. Applications which might warrant higher fidelity models also mandate much tighter synchronization to support the model complexity.

From the perspective of optimal design it is convenient to tie δG_n^r and δG_n^{r*} into a single performance metric. This is a very application dependent choice, but in the case of our example we decided to penalize increasing model fidelity against the product of the growing error norm due to clock uncertainty and increasing computing cost expressed as simulation time in seconds T_{sim}. The optimal choice being the intersection of the trajectories of δG_n^r and $(\delta G_n^{r*} \times T_{sim})$. Figure 8 shows this design tradeoff, indicating that the optimal design for our use case is a model with 45 π-sections.

VI. CONCLUSION AND FUTURE WORK

This paper presents an argument for introducing clock accuracy and synchronization early in the design phase when

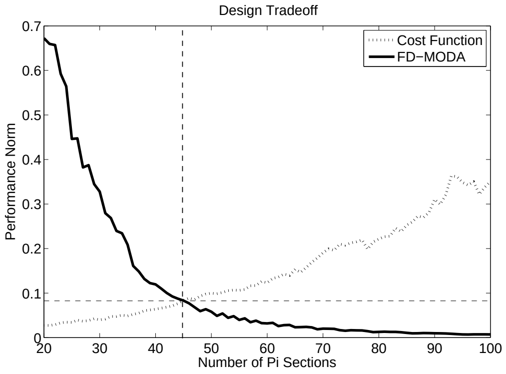

Fig. 8. Optimal model choice at the intersection of δG_n^r and $(\delta G_n^{r*} \times T_{sim})$.

the mathematical model of the system is being developed. We show that using clock accuracy to guide model synthesis results in a different optimal design than without. The results in Section V illustrate this through an application where a mathematical model of an electrical transmission line is capped at 48 π-sections as opposed to a more complex model with 86 π-sections without considering the effects of clock jitter and accuracy at higher sampling frequencies. Essentially, this is tantamount to saying that these two models are equally effective when used in a network with the given clock accuracy. This is a useful result because it clarifies the intuitive impression that there are practical limits when mathematical models are used to control real systems with distributed clocks. Over a distributed system in the scale of the energy grid the potential benefits of these simpler models are clear. However, it is also interesting to note that the choice of clock accuracy, including the choice to adopt PTP versus NTP (the Network Time Protocol), can be based on simulation results from prevalent methods such as FD-MODA used here. We conclude that much like network jitter, delay, and actuator/sensor limits are variables considered during model synthesis, the addition of expected clock accuracy across the distributed system is an important design variable.

The cost penalties we applied to our model when the system frequencies approach the clock accuracy are based on empirical results derived from our previous work in [18] and [22]. This varies depending on the choice of system and does draw from some engineering insight on the part of the designer. Our future work will be to extend this idea to a general class of linear systems along the lines of work presented in [19]. We would like to be able to provide a set of model synthesis tools to engineers and designers so that clock synchronization moves from being a consideration purely during implementation to being one of the factors influencing early design choices and mathematical modeling.

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