A Framework of Smart and Secure Power Electronics Driven HVAC Thermal Inertia in Distributed Power Systems

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***Abstract*—This paper explores a framework of combining expertise in power electronics, power systems, and cyber-physical security to tackle future inertia lacking and security concerned smart grids. In particular, power electronics and motor driven building HVAC systems serve as an investigation example. Dynamic room temperature adjustment without sacrificing occupants' comfort is an effective but virtual bi-directional form of energy storage, creating useful power systems inertia. First order control realized inertia at a 10 s to 15 min timescale is reviewed, and second order inertia at a sub-second scale is proposed, behaving as a virtual synchronous machine (VSM). Simulation results of local HVAC drive' dynamic responses as well as IEEE 118 bus systems containing such VSM's demonstrate the effectiveness. Internet data driven HVAC microcontrollers, replacing any conventional local communication, expose vulnerability to hacking. Cyber security measure is proposed to prepare such IoT devices to become online.**

***Index Terms*—HVAC thermal storage, thermal inertia, power electronics and drives, distributed power systems, energy efficient buildings, smart grids, cyber physical security, IoT devices**

I. INTRODUCTION

As increasing amounts of power electronics interfaced renewable resources and lower-inertia distributed generation are becoming integrated into power systems, enabling smarter grids and more intelligent and connected communities, a documented problem arises from the lack of inertia provided to the system by these resources [1]. The current trends leading toward declining system frequency response are well-documented, and this lack of frequency response threatens the reliability of the grid. Lower grid inertia means that small events will result in larger frequency excursions and in greater burden with extra wear and tear on generator governors [2].

In this paper, we present a framework for utilizing hybrid battery and smart building HVAC (heating, ventilation, and air conditioning) systems, with an emphasis on the latter, to provide storage at multiple time scales. We introduce a residential level distributed inertia, namely virtual bi-directional thermal storage as thermal inertia, to mimic a virtual synchronous machine to improve power system frequency response. In addition to the seconds-scale dynamics, the hybrid storage is effective in minutes-scale as large energy reserves so that the conventional battery size and cost is drastically decreased.

After presenting how distributed inertia can be feasibly provided as a resource for power systems through the presented coupled models, we describe the steps required to ensure its secure and trustworthy realization in practice. A section of this paper focuses on cyber-physical resilience with respect to potential cyber physical intrusion on power electronic energy systems. Related issues have raised awareness at the U.S. federal government level [3]. Secure and resilient control and communications are a key factor in realizing this solution at a city-wide level and at an inter-city level.

II. POWER ELECTRONICS IMPLEMENTED HVAC BASED THERMAL STORAGE AS EFFECTIVE THERMAL INERTIA

An emerging research effort is utilizing building HVAC systems to provide demand response, effectively offsetting grid dynamics between 10 seconds and 15 minutes and essentially acting as ancillary services [4]-[5]. The principle behind is to adjust buildings' thermal energy storage in the form of room temperature without sacrificing occupants' comfort as a result of regulating intake electrical energy. In general, a slower timescale results in a larger temperature variation, and a faster timescale is limited by hardware response capability. Paper [6] brings the HVAC thermal storage concept in depth regarding the implementation from the power electronics perspective. In particular, 1) a formal definition of virtual bi-directional thermal storage and thermal inertia is created by setting a virtual steady-state operating point and supplying energy back to the grid virtually under sub-nominal operating conditions; 2) HVAC systems low-pass filter noisy buildings' rooftop solar generation that is under maximum power tracking before feeding a smoothened power curve to the grid; and 3) several experiments discovered motor drives and electric machines' maximum slew rates, swing bands, and associated acoustic noise through fans and ducts.

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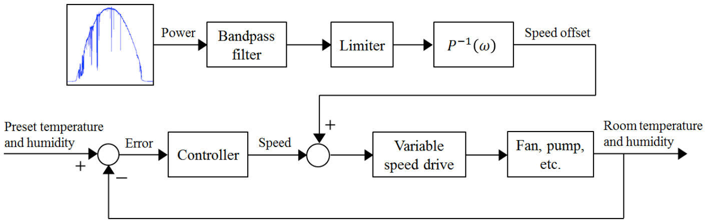


Fig. 1. Block diagrams of HVAC adjustment for dynamic thermal storage [6].

In [6], a first-order feedback loop is proposed and proved for its effectiveness for thermal inertia, as illustrated in Fig. 1. However, one question is left open; that is, what does it take to implement a second-order feedback loop to effectively provide frequency and reactive power compensation, more effectively during transients at sub-second time scales? A separate paper [7] modifies from existing virtual synchronous machine (VSM) research [8]-[9] to create a second-order thermal inertia with enclosed passenger space in more electric aircraft power systems. A similar approach can be realized in the HVAC motor drives, which consist of an AC-DC front end, a DC link, and a DC-AC inverter driven motor. The advantage of this approach is that any existing HVAC hardware stays intact while only modifying the control firmware. Fig. 2 highlights the VSM based thermal storage. As indicated by the dotted outline, the power electronics, passive components, motors, and thermal storage integrated as a whole behaves as a VSM seen from the grid side. There are two major parts – the active front end, which is from the DC link to the grid interface point, and the motor/inverter side, which is here on the left side of the DC link.

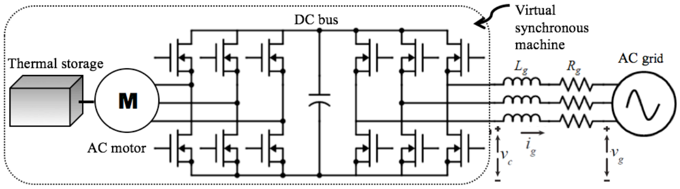


Fig. 2. High-level VSM based thermal storage [7].

In order to obtain the converter modulation indices, the front-end converter three-phase output voltage signals (v_{ca}, v_{cb}, v_{cc}) are calculated from the control diagrams in Fig. 3, given the instantaneous output currents (i_{ga}, i_{gb}, i_{gc}) and rotating frequency (ω_g), as well as desired real power (P_{ref}) and reactive power (Q_{ref}). The main equations are the VSM torque (τ) and angle (θ) calculations, including the damping factor (D), where J is the virtual moment of inertia of this front-end converter, and p is the pole pair. Note that J, p, D, and M values can be arbitrary but should be chosen in realistic ranges so that the converter performance is not compromised. For detailed equation derivations, see [7]-[9].

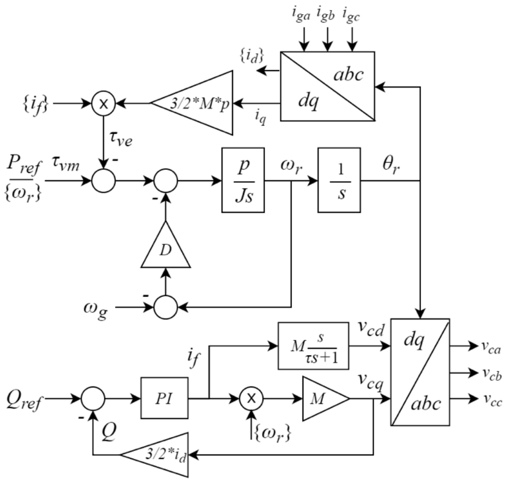


Fig. 3. Control blocks of VSM utilizing a hex-bridge converter. (“{ }” indicates intermediate variables but not system inputs or outputs.)

To work in synchrony with the active front end, the AC motor-tied inverter (i.e., the left hex-bridge converter in Fig. 3) has the purpose of maintaining a constant DC bus by adjusting the motor speed and torque using conventional vector controls. The DC bus voltage incurs small voltage changes, and hence energy changes, due to the front end converter reacting to the main generator. The control blocks are described in Fig. 4.

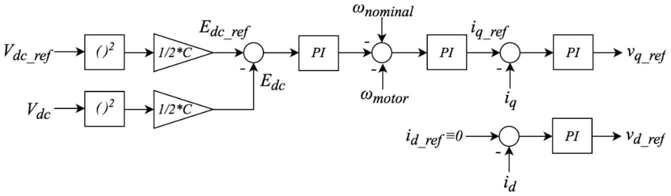


Fig. 4. Diagrams for inverter/motor to maintain DC bus voltage.

III. INTEGRATION OF THERMAL STORAGE INTO POWER SYSTEMS AT MULTIPLE TIMESCALES

The power electronics implemented HVAC drives as a VSM has demonstrated how a response to a load disturbance is realized, locally. Then how does the interconnected grid view this VSM or a cluster of such VSM’s, as power system nodes, in response to a large network generation disturbance? In recent work, the potential of committing distributed energy resources is demonstrated. These resources are also referred to as Autonomous Interruptible Load (AIL) resources. As mentioned in [10], the communication delays and costs are currently prohibitive for centralized control and thus should operate based on local frequency measurements. Frequency response must operate quickly to be effective. In this work, the AIL resources are modeled as variable constant impedance load models connected to under-frequency relays with a limit of 59.2 Hz. Fig. 5 shows a before and after simulation of improved frequency responses with utilizing VSM’s as part of the distributed inertia resources.

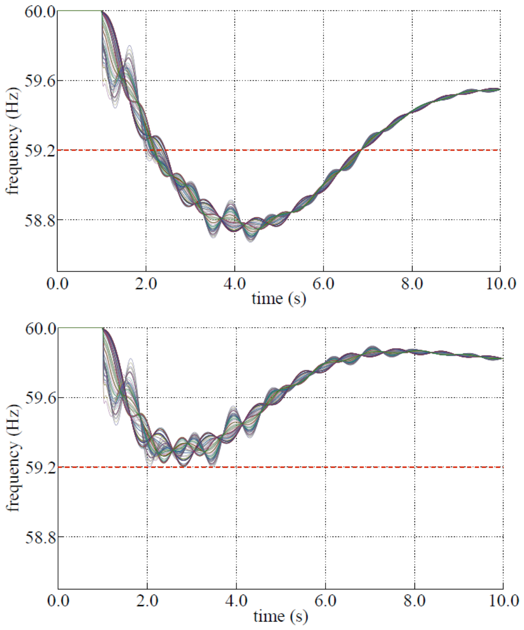


Fig. 5. IEEE 118 bus system: top – simulated baseline frequency response, bottom – simulated use of distributed inertia resources to improve frequency response [10].

In general, the interface between a machine model (or in this case, a virtual machine model) and the rest of the power system can be described in terms of the voltage and current at the terminals as well as the differential and algebraic equations of that model. In analyzing transient stability for large-scale power systems, the solution is computed via explicit integration using, for example, Runge Kutta. The virtual thermal storage model (VTSM) can thus be directly coupled with a full-order large-scale dynamic model of the interconnected power system.

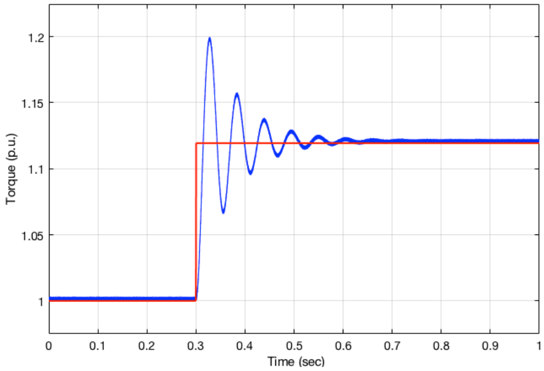


Fig. 6. VSM active front end virtual torque response.

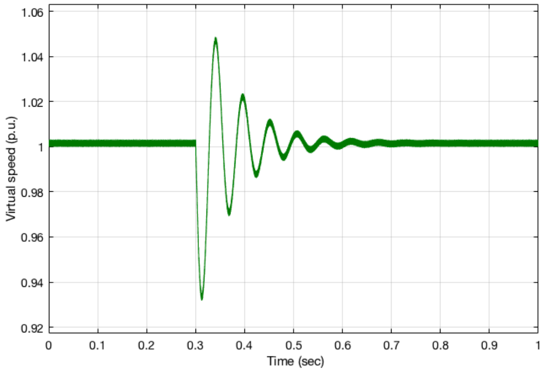


Fig. 7. VSM active front end virtual rotating speed response.

To initialize this model, the network interface's initial terminal voltage and current (both real and imaginary parts) are passed into the model. During initialization, the VTSM must set/return its initial d-axis current I_d and q-axis current I_q. The VTSM model must also provide its Thevenin or Norton equivalent parameters. The transient stability engine in PowerWorld Simulator then maintains these I_d and I_q as state variables during solution. The VTSM model also returns the machine speed deviation from synchronous. Normally, this is passed into a machine's governor model. The machine's field current and electrical torque are also to be returned. The field current is normally passed into the machine's exciter model.

An example simulation study is performed on VSM control to respond to grid connected dynamics. Fig. 6 shows a virtual torque response at the VSM active front end given a desired torque step requirement. The response appears underdamped here because of a relatively small virtual damping coefficient chosen. To better understand the behaviors of the VSM, the virtual rotating speed, real power and reactive power compensations are plotted in Fig. 7, Fig. 8, and Fig. 9, respectively. When a larger damping coefficient is selected, an overdamped response returns. In these plots, it can be observed that the dynamic behaviors resemble those from a real synchronous machine except for the fast switching generated from the power electronics.

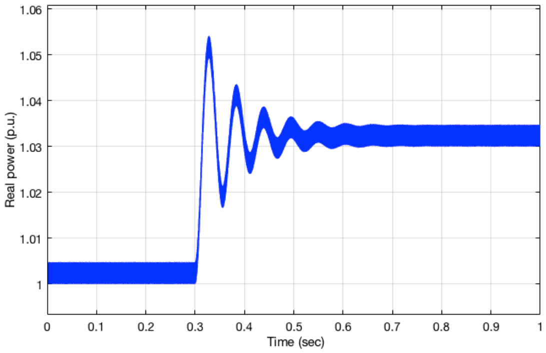


Fig. 8. VSM real power variations.

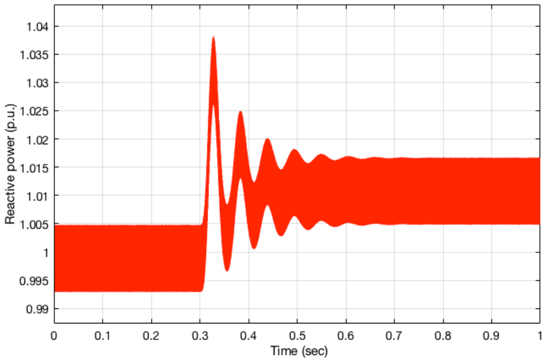


Fig. 9. VSM reactive power variations.

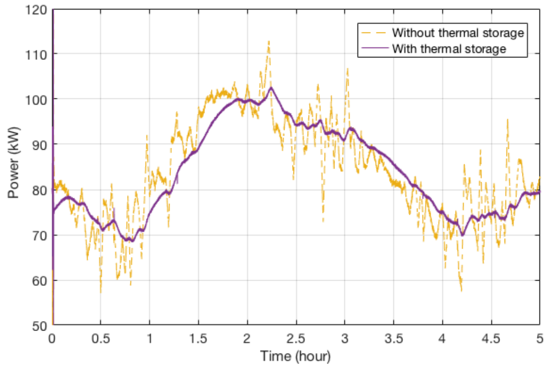


Fig. 10. A building side's local power deman with and without HVAC thermal inertia for a 5-hour simulation experiment.

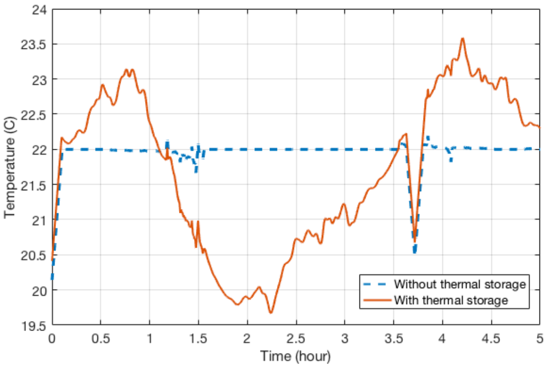


Fig. 11. Room temperature variations during the experiment.

As mentioned before, the HVAC thermal storage acts as effective inertia in multiple timescales. Fast transients have been discussed. The building connected grid side also avoids power variations in the bandwidth of 1 mHz to 0.1 Hz (inverse of 15 min to 10 s), subject to slew rate and maximum fan speed to deter hardware wear and tear as well as human acoustic discomfort. For this work, the discussed power electronics control laws for thermal storage integration are incorporated with a renewable energy powered energy efficient building power system model. A load profile includes stochastic, light and heavy, fast and slow, electrical load changes, which can be negative given the onsite renewable energy generation.

Fig. 10 shows grid side power demand with and without the HVAC thermal storage mitigation of load power variability. Because of the feasible bandwidth of this thermal inertia, dynamics faster than 1 Hz or slower than 15 minutes may seek buffering from conventional batteries. From Fig. 10, it can be observed that throughout the load profile, short periods of power variations up to 20 kW are mitigated, out of total nominal 100 kW, resulting in a relatively constant required grid power. This potentially allows the reduction of building side battery storage while relying on spinning reserves. In Fig. 11, room temperature from a thermal model [5] is plotted for both scenarios, with and without HVAC thermal inertia. It can be observed that there are periods of up to 3 °C changes due to long and large power variations, while during the majority of the profile only minor temperature fluctuations occur.

In [6], it has been demonstrated that for a particular energy efficient building, a total of 53.0 kWh battery energy is required for grid support when HVAC thermal storage is not engaged. With HVAC for dynamic energy regulation, this number drops to 39.1 kWh, a 26% reduction.

IV. CYBER SECURITY MEASURE IN POWER ELECTRONICS BASED ENERGY SYSTEMS

Energy converting power electronics consist of power circuitry and control hardware. Traditional power electronics controllers, in HVAC systems for example, have on-board embedded firmware to command the motor drives to update operations locally, to fulfill one or a few rooms' comfort demand. Already common in recent energy-efficient buildings, the building's central computer sends building usage data to HVAC controllers via communication protocols such as Modbus. This current intranet operation will expand to be internet or cloud based in the smart energy community, since such controllers must be online communicating with other sensors and controllers in real time. The HVAC system's power electronics microcontrollers, no longer isolated as before, will require advanced cyber security protection to avoid manipulated damages to the building as well as the connected grid.

Because HVAC systems consume approximately 40-60% of a building's electrical energy, a wide-area attack of drastic energy manipulation can cause potentially severe consequences at a range of levels. In addition to consequences that affect individual buildings (where we can quantify the resulting loss of energy and thus productivity of a building), distributed coordinated attacks on increasing amounts of HVAC can create localized distribution system problems that are detrimental to city level performance. Transmission level consequences of a city-level threat, especially if such a threat extends beyond a single city, must be considered and defended against as well. Similar scenarios apply to other power electronics controlled batteries or any distributed energy resource.

IoST implements an easy-to-use capsule distribution and installation interface for nontechnical users, power operators, and capsule owners. The capsules are distributed via IoST's server that is also in charge of certificate issuance as well as controller program vetting regarding the physical plant's safety constraints (Fig. 12). Our distribution scheme aims to allow capsule owners to create capsules and define policies they would like to enforce on their data as well as to allow users to aggregate multiple capsules in a persona. The IoST's capsule distribution framework includes a platform verification procedure to verify the genuineness on the embedded IoT devices to make sure that policies will be correctly enforced by the system on the corresponding data capsules [11]-[12].

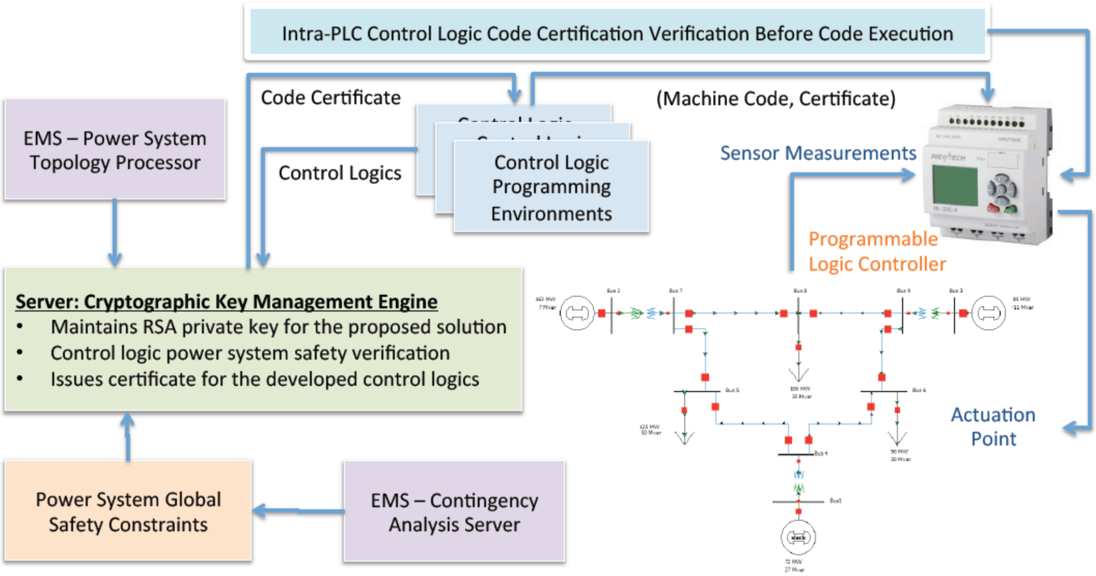
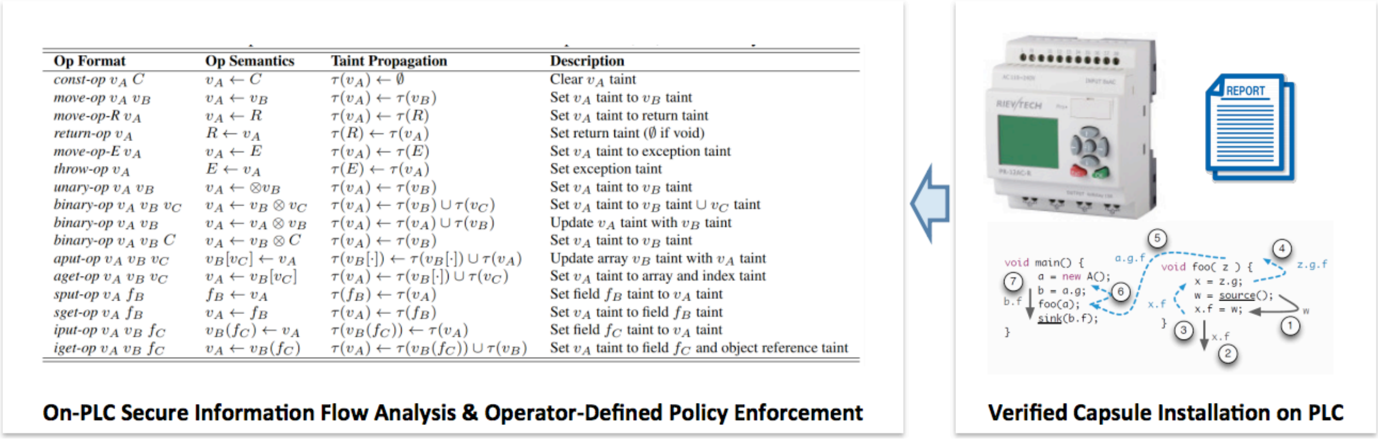


Fig. 12. High-level cyber architecture, its components and their logical interconnections.



Op Format	Op Semantics	Taint Propagation	Description
const-op v_A C	$v_A \leftarrow C$	$\tau(v_A) \leftarrow \emptyset$	Clear v_A taint
move-op v_A v_B	$v_A \leftarrow v_B$	$\tau(v_A) \leftarrow \tau(v_B)$	Set v_A taint to v_B taint
move-op-R v_A	$v_A \leftarrow R$	$\tau(v_A) \leftarrow \tau(R)$	Set v_A taint to return taint
return-op v_A	$R \leftarrow v_A$	$\tau(R) \leftarrow \tau(v_A)$	Set return taint ($\emptyset$ if void)
move-op-E v_A	$v_A \leftarrow E$	$\tau(v_A) \leftarrow \tau(E)$	Set v_A taint to exception taint
throw-op v_A	$E \leftarrow v_A$	$\tau(E) \leftarrow \tau(v_A)$	Set exception taint
unary-op v_A v_B	$v_A \leftarrow \otimes v_B$	$\tau(v_A) \leftarrow \tau(v_B)$	Set v_A taint to v_B taint
binary-op v_A v_B v_C	$v_A \leftarrow v_B \otimes v_C$	$\tau(v_A) \leftarrow \tau(v_B) \cup \tau(v_C)$	Set v_A taint to v_B taint $\cup$ v_C taint
binary-op v_A v_B	$v_A \leftarrow v_A \otimes v_B$	$\tau(v_A) \leftarrow \tau(v_A) \cup \tau(v_B)$	Update v_A taint with v_B taint
binary-op v_A v_B C	$v_A \leftarrow v_B \otimes C$	$\tau(v_A) \leftarrow \tau(v_B)$	Set v_A taint to v_B taint
aput-op v_A v_B v_C	$v_B[v_C] \leftarrow v_A$	$\tau(v_B[\cdot]) \leftarrow \tau(v_B[\cdot]) \cup \tau(v_A)$	Update array v_B taint with v_A taint
aget-op v_A v_B v_C	$v_A \leftarrow v_B[v_C]$	$\tau(v_A) \leftarrow \tau(v_B[\cdot]) \cup \tau(v_C)$	Set v_A taint to array and index taint
sput-op v_A f_B	$f_B \leftarrow v_A$	$\tau(f_B) \leftarrow \tau(v_A)$	Set field f_B taint to v_A taint
sget-op v_A f_B	$v_A \leftarrow f_B$	$\tau(v_A) \leftarrow \tau(f_B)$	Set v_A taint to field f_B taint
iput-op v_A v_B f_C	$v_B(f_C) \leftarrow v_A$	$\tau(v_B(f_C)) \leftarrow \tau(v_A)$	Set field f_C taint to v_A taint
iget-op v_A v_B f_C	$v_A \leftarrow v_B(f_C)$	$\tau(v_A) \leftarrow \tau(v_B(f_C)) \cup \tau(v_B)$	Set v_A taint to field f_C and object reference taint

On-PLC Secure Information Flow Analysis & Operator-Defined Policy Enforcement

```
void main() {
    a = new A();
    b = a.g;
    foo(a);
    sink(b.f);
}
```

```
void foo( z ) {
    x = z.g;
    w = source();
    x.f = w;
}
```

Verified Capsule Installation on PLC

Fig. 13. Dynamic information flow analysis.

IoST performs similar information flow tracking on the IoT device for the control logic program executions on its firmware. The goal is to determine the set of inputs to the device and sensitive data sources that affect the value of each output value from the IoT device to the underlying plant actuators. Real-time maintenance of such fine-grained information flow allows IoST to facilitate security access control policies within the system, whenever unauthorized data accesses and modifications are about to happen. For instance, a power system-safety policy may allow modification of certain output ports or read access of a certain confidentiality-sensitive input sensor port on the IoT device by only the control logic programs that are developed by certain authorized operators. Dynamic information flow tracking allows IoST to detect and block whenever a control logic program developed by a certain developer tries to access a sensitive input port, or write to a certain output port. The verification of the control logic program developers can be done by IoST's server and through a cryptographic public/private-key certificate-based validation (Fig. 12). The dynamic information flow tracking is implemented following a sequence of data flow ruleset as shown on left side of Fig. 13. Individual instruction execution may result in a low-level data flow between memory addresses and registers, and hence requires an update to the taint propagation shadow memory.

V. CONCLUSION

In this paper, we presented building HVAC enabled thermal storage as effective inertia in distributed power systems, served as an example of integrating power electronics, power systems, and cyber security knowledge domains. The thermal inertia is able to mitigate fast dynamics, at a second to subsecond timescale, behaving as virtual synchronous machines given a disturbance in the connected power systems. The control acts on existing three-phase motor drives at the active front end as well as the DC bus connected inverter. The thermal inertia is also valid on a 10 s to 15 min timescale to filter user-end or renewable energy generated stochastic loads so that the grid side views a smoothened loading profile as regular ancillary services kick in. Without drastic temperature variations, acoustic annoyance, or hardware wear and tear, this thermal storage is virtual bidirectional replacement of a significant fraction of existing storage requirement, such as batteries. Future smart communities include cloud-based data-driven HVAC controls. Power electronic microcontrollers are prone to hacking, and cyber-physical security measures must be ready before such IoT devices become online.

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