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Published in:

Proceedings of PCIM Europe 2015; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management

Publication date:
2015

Document Version
Early version, also known as pre-print

[Link to publication from Aalborg University](#)

Citation for published version (APA):

Xue, Y., & Guerrero, J. M. (2015). Smart Inverters for Utility and Industry Applications. In *Proceedings of PCIM Europe 2015; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management* VDE Verlag GMBH.
http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7149047&queryText=Smart+Inverters+for+Utility+and+Industry+Applications&newsearch=true&searchField=Search_All

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Smart Inverters for Utility and Industry Applications

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Abstract

Smart inverters are emerging with increasing renewable energy and smart grid development. While the recent work reviewed mostly focuses on defining standardized control functionalities and smart grid communication protocols, we take a holistic approach in this paper and propose a holon-type smart inverter concept, which features autonomous, adaptive, cooperative and plug-and-play functions. Self-awareness is also continually driven by power electronics inherently. These features can be favorable in a complex environment with more and more small-scale power electronics-based devices, and can reduce system control and communication requirements during both normal and faulty operations. Challenges may present when multiple distributed inverters are required to collectively achieve a common goal. With Industry 4.0, it is expected that smart inverters will be highly demanded at conversion and connection levels in smart manufacturing environment.

1. Introduction

Power electronics are approaching maturity from the internal driving philosophy. It is recognized [1] that the further development of the constituent technologies of power electronics is driven by emerging applications. Apart from continuous self-driven motivations of being more reliable, more efficient, more compact and less costly, new utility and industry applications have demanded smart features associated with power electronics, especially power inverters, hence the term "smart inverter". These applications mainly spread within utility power and manufacturing industries.

Beyond smart grids, utility power systems are experiencing divergent grid modernization with transition toward a decentralized and distributed grid structure. The technologies, solutions and business models advancing this initiative are termed as "the grid edge", where power electronics plays unique and crucial roles [2]. For early time low-penetration renewable energy systems, power inverters serve basic functions of power conversion and energy feeding, and will disconnect from the grid during abnormal grid conditions or power outage. With more and more grid integrations of small-scale distributed generations (DG), e.g. residential solar photovoltaic (PV) inverters, the power quality issue at the interconnection point becomes eminent, and hence multi-functional inverters are developed to provide certain ancillary services and local voltage support functions. Recently with the need of smart grid interoperability, power industry has initiated to develop a set of standardized inverter functions to facilitate the deployment of large quantities of distributed generations and to mitigate the frequency issue associated with the parallel tripping of solar PV inverters, known as the "50.2 Hz problem" in Europe. In these efforts, the focuses are more towards smart grid interoperable well-defined protocols and standardized functionalities, leading to smart grid ready inverters. Furthermore, autonomous operations of emerging microgrids demand for new control functionalities of power converters [3].

Similarly, manufacturing industry is undergoing a transition to smart manufacturing or the 4th industrial revolution, i.e. Industry 4.0 as referred in Germany. Smart manufacturing relies on cyber-physical systems (CPS) and the Internet of Things. Within the architecture of a CPS [4], smart machines, including sensors, components and inverters, fit in with the bottom two levels, i.e. connection and conversion levels, which require plug-and-play, condition monitoring, prognostics and health management (PHM). Although today's inverters have already embedded with fault diagnoses to certain extent, the fault inclination and lifetime of power semiconductors and electrolytic capacitors remain concerns for power electronics. Therefore smart inverters with self-optimization, self-configuration and self-awareness can be very promising in future smart manufacturing applications.

In this paper, we use a holistic approach to define what a smart inverter should behave, more specifically as autonomous body like a holon, a term used in philosophy to describe something simultaneously as a whole and a part. The state-of-the-art smart inverter development will first be reviewed, and five major features of a smart inverter are discussed with a proposed functional model. Furthermore discussions will be extended to technical trends that contribute to smart inverters and potential challenges as well as applications.

2. The State-of-the-Art Smart Inverter Concepts

With power deregulation, there is a demand for distributed generations to provide ancillary services. Among those, research efforts are mostly focused on developing smart solar PV inverters [5]. Beyond maximum power-point tracking, islanding detection and basic energy feeding and power conversion functions, smart or multi-functional PV inverters provide additional capabilities of fault ride-through, reactive power compensation, and local power quality and stability enhancement. To seamlessly integrate the PV systems into smart grid, the US Department of Energy has launched an effort [6] to develop advanced PV inverter systems with intelligent, interactive, and dispatchable functions so that solar power can be integrated into grid management.

While these developments continue, electric utilities have already experienced operation challenges due to high penetration solar power occurring at low demand and frequency stability issues due to significant amount of instant tripping of traditional PV inverters connected to low voltage distribution network. In Germany, the study of "50.2 Hz problem" suggests technical retrofitting of existing PV inverters with frequency-dependent active power control and stochastic reconnection. In USA, California utilities have foreseen the phenomenon of "duck curve", which depicts the over generation of solar power and reduced net load between 11am-2pm and rapid ramping up or conventional power in the afternoon hours. California Public Utilities Commission has recently initiated a Smart Inverter Working Group to investigate the new requirements required for inverter-based solar PV and energy storages. The resulted recommendations [7], including 8 autonomous functions, communication requirements and additional advanced functions using communications, now have been approved to be included in the California's Electric Tariff Rule 21, which governs the distributed energy resources interconnection in California utilities.

With the extension of smart inverter concept to any type of power electronics based DGs, common and standardized functions become necessary. The document [8] developed by the Electric Power Research Institute in the USA has defined a set of common functions for smart inverters in the integrated grid. In the meantime, a few IEEE and IEC standards are under revision or new development. IEEE 1547, the recommended interconnection standard for distributed generations below 10 MVA, is currently under full revision. IEEE 2030 and its series are under development to provide a guide for smart grid interoperability of distributed energy resources (DER) operation with the electric power system. IEC TC57 WG17 is developing the communication architecture for integrating DER into IEC 61850 body of communication standards. IEC technical report, IEC/TR 61850-90-7, describes advanced functions object modeling for power converters in DER systems, which will be adopted in the new edition of IEC 61850-7-420, the first standard for DER object modeling.

As reviewed, the smart inverter development so far is primarily limited to utility sector with high penetration renewable scenario and smart grid environment. Other distributed deployment applications, e.g. industry and manufacturing, are yet to be investigated.

3. A New Definition of Smart Inverters

3.1. Five Major Features

With the proliferation of distributed generations and automations, existing centralized control, communication and operation resources may not be able to accommodate such a complexity. Various distributed control architectures have been proposed, e.g. multi-agent system (MAS), holonic MAS, and service-oriented architecture, but imposed challenges like decomposition and global performance when applied to complex power systems. Irrespective of control architectures, autonomous, adaptive, functionally scalable and plug-and-play sub-systems are highly desired to reduce the requirements of control and communications and to relieve the system operation burden. A holon, as described by Arthur Koestler in 1967, is a part-whole system, with an evolving self-organizing dissipative structure, that can be seen as a component of a higher level system or as a whole composed of other holons. Here we generalize a smart inverter as a holon possesses the following five desired features:

Self-Awareness

Self-awareness is becoming important for decentralized systems to achieve advanced levels of autonomous behavior [9]. Here we define a system with self-awareness possesses information about its internal state, i.e. private self-awareness. For smart inverters, self-awareness aims to improving operational reliability and predicting the lifetime, thus enabling fail-safe or maintenance actions and effectively avoiding catastrophic accident in safety critical systems using power electronics.

Over the decades, there have been various diagnostic techniques [10] developed to detect, isolate, and identify faulted power semiconductor devices. In recent years, the trend is moving towards the condition monitoring of converter core components such as power devices and electrolytic capacitors based on real-time operating parameters [11] with the goal to evaluate the component aging and current health level. Combined with lifetime prediction, smart inverters achieve overall prognostics and health management.

Furthermore, it is expected that future smart inverters own certain degree of intelligence, e.g. knowledge of its role or importance within its environment and the likely effect of potential future actions, i.e. meta-cognition, and self-expression.

Adaptability

Adaptability is the ability of a system to adapt itself efficiently and fast to changed circumstances or changes in parts of the system itself. Smart inverters can be designed to be control-adaptive, frequency-adaptive, impedance-adaptive, and fault-tolerant. Self-tuning controller using adaptive law, e.g. adaptive MPPT, adaptive droop control, and adaptive current control, can achieve Lyapunov stability under uncertainties and wide operating conditions. For grid applications, frequency-adaptive phase-locked loop can effectively track and synchronize with the grid under various non-ideal grid conditions such as distortion, unbalance and dynamics (frequency drifts and phase angle jumps). Grid impedance estimate is also necessary for grid-connected inverters to choose appropriate operation mode and properly decouple active power and reactive power. Fault-tolerant inverters are typically implemented in the design by hardware redundancy [12] at device, leg, module, or system level and involve fault isolation, fault reconfiguration and fault-tolerant control on the run.

Autonomy

Autonomy is defined here as the system being smart enough to decide its own operation mode. Autonomous behavior is a basic property for a distributed system. Nowadays automation is moving from traditional vertical and centralized hierarchy to more parallel and distributed CPS-based structure. Being part of a cyber-physical system, smart inverter with autonomous operation can be necessary in case of limited or no communication, or if desired for reliability. One common scenario is autonomous load power sharing using droop methods [13] when multiple inverters operate in parallel. For autonomous operation of an inverter-based microgrid, smart inverters shall achieve capabilities such as dynamic grid feeding, dynamic grid forming, black start, seamless power transfer, and power quality enhancement. Other autonomous functions in [7,8] are required by the power utility for distributed generations.

Cooperativeness

The complexity of decentralized energy and automation systems make it necessary to realize cooperative controller in individual smart inverter while each of them assumes some responsibilities maintaining system stability and quality, and multiple of them are seeking to achieve a desired collective objective within the system or neighboring subsystem. As opposed to centralized solutions, communications among neighboring smart inverters may be needed and locally gathered information is distributed to neighbors. Such a distributed control and decision architecture not only relaxes the need of centralized controller, but potentially results in benefits like self-organization and robustness to dynamic uncertainties. Cooperative control can be applied to smart inverters with modular structures for fault tolerance and scalability, operating in a microgrid achieving plug-and-play [15] or in active distribution systems for optimal voltage regulation.

Plug-and-Play

Plug-and-play (PnP) is the ability for a smart inverter to add to a system and operate automatically without technical configuration. The PnP operation can be achieved either with communication or without communication, resulting in system benefits of scalability, interoperability, resilience, and reliability. Although widely used in computing interfaces and industry field buses, the PnP concept was introduced only recently in power electronics [14] to achieve distributed intelligence based on power electronics equipment. PnP can be implemented at the power converters with modular hardware structures and the smart inverters for microgrids for distributed frequency/voltage regulation and smart grids for distributed voltage control. Standardized communication protocols and unified control interfaces are currently under discussion for utility applications with the recommendations of using IEC 61850-7-420 and -90-7 for data object models, Smart Energy Profile 2.0 (SEP2) as the leading candidate utility communication protocol at application layer, and Internet protocol TCP/IP at transport level, according to California smart inverter working group.

3.2. Hardware Structure and Functional Model

Smart inverters owns the fundamental functions of power electronics technology, which are characterized in [1] as switching function, conduction function, electromagnetic energy storage function, information function, heat exchange function, and mechanical/structural function. On top of these internal functions, the abstract smart features will be realized by a variety of control functions or hardware approaches, most of which have been developed in the literature for specific applications. Here we attempt to attribute them to individual smart feature as listed in Fig. 1.

A general smart inverter control structure is shown in Fig. 2, which features with an autonomous controller, a cooperative controller, and an optional transactive controller for market price signal.

A generalized smart inverter hardware structure is illustrated presented in Fig. 3 along with the control and protection functionalities corresponding to each hardware and control layer. The internal control hierarchy can be categorized based on time scale from low to high as hardware control level, switching control level, converter control level, application control level, and system control level, adopted from IEEE Std. 1676-2010, with protection functions across all control levels.

Although a smart inverter aims to operating in a decentralized control environment, it does not restrict itself to any specific system control architecture. Practically the hierarchical architectures are more prone to be adopted. As an example, a four-layer hierarchical structure composed of holons, a holarchy, can be used to model a microgrid with multiple feeders and multiple smart inverters, as illustrated in Fig. 4. Each layer is associated with specific control objectives, which requires collective efforts from its sub-holons, e.g. at the feeder level, permissible voltage shall be guaranteed.

Smart Features	Possible Approaches or Control Functions
Plug-and-play	<ul style="list-style-type: none"> • Standardized communication protocols • Non-formation cooperative controller (distributed frequency control, parallel processing, etc.) • Communication graph (at cyber layer)
Self-awareness	<ul style="list-style-type: none"> • Fault diagnostics (detection, isolation and classification) • Prognostics & health management (condition monitoring and device lifetime estimation) • Self-expression with communication (alarm, status, etc.)
Adaptability	<ul style="list-style-type: none"> • Grid parameter estimation • Frequency-adaptive grid synchronization • Distributed anti-islanding detection and adaptive mode transfer • Real-time optimization • Fault tolerance (modular and redundant structure, fault current control, fault ride-through) • Current source/voltage source flexibility
Autonomy	<ul style="list-style-type: none"> • Active/reactive power flow control • Grid forming/grid following flexibility
Cooperativeness	<ul style="list-style-type: none"> • Dynamic grid feeding • Dynamic grid supporting • Active/reactive power and harmonic current sharing • Sub- or super-harmonic damping • Ramp rate control • Soft start • Coordinated harmonics compensation • Coordinated unbalance compensation

Fig. 1. A list of control functions and approaches associated with each smart inverter feature.

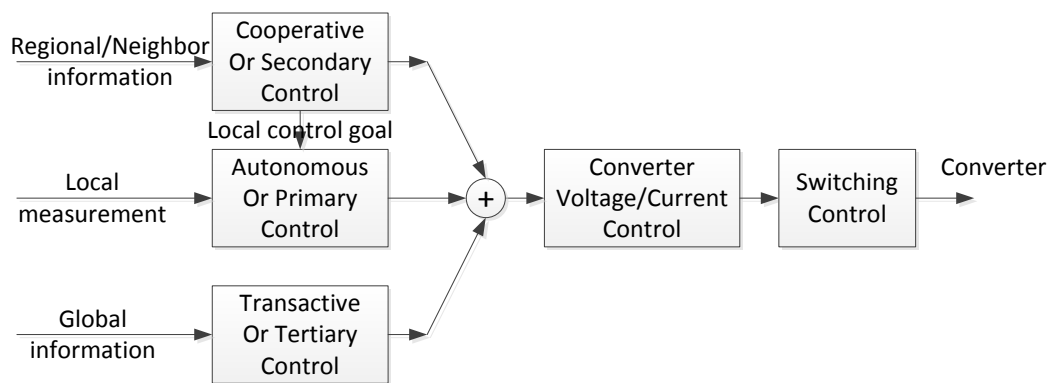


Fig. 2. General control structure of smart inverter.

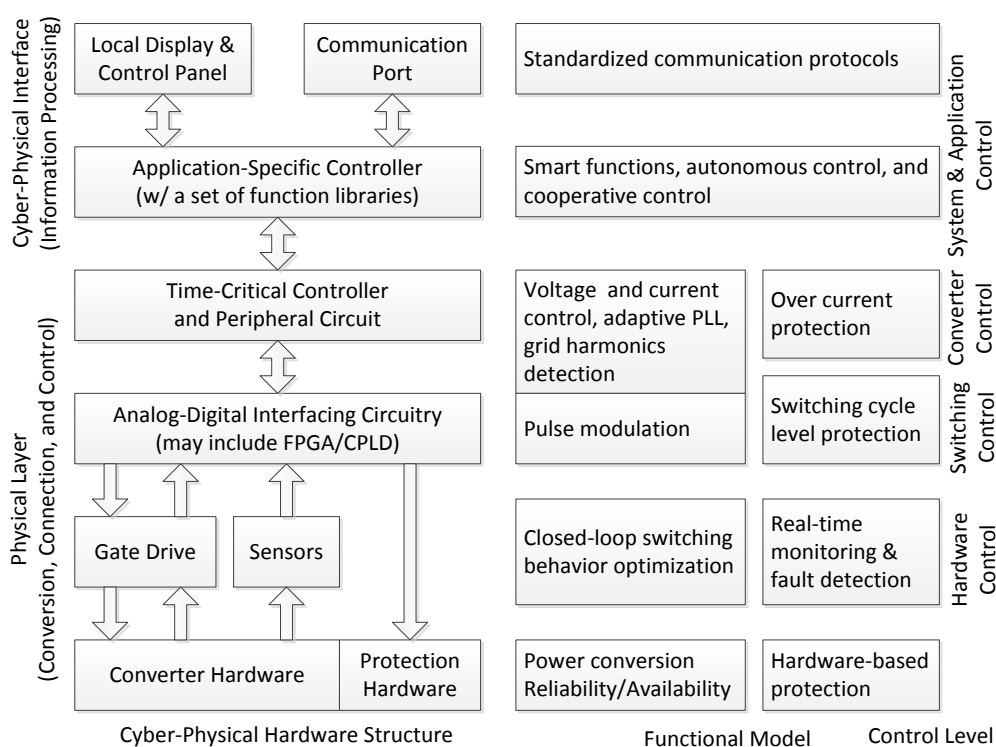


Fig. 3. A generic smart inverter hardware structure and corresponding functionalities.

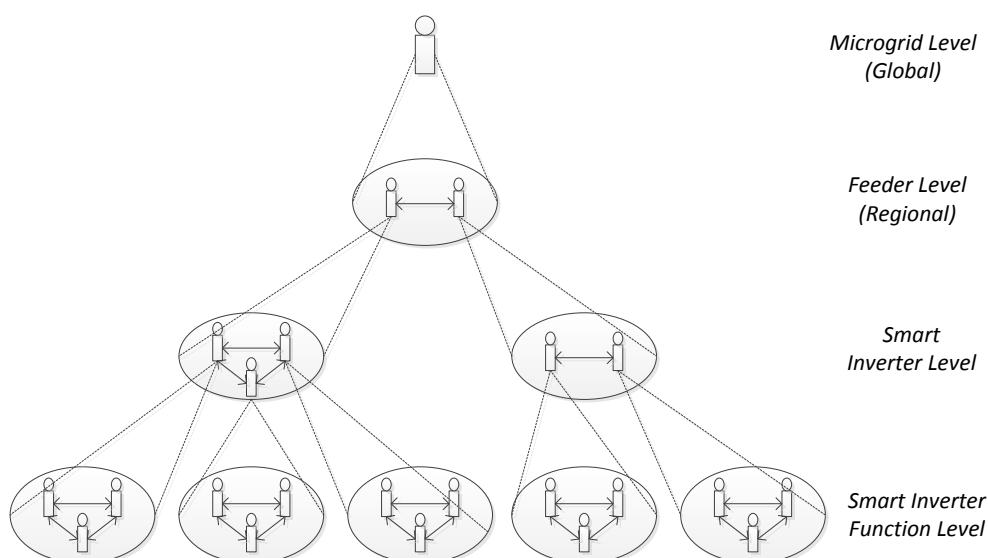


Fig. 4. Smart inverter-based holonic microgrid architecture.

4. Challenges and Trends

4.1. Challenges

Three major technical challenges can be identified for a smart inverter to realize certain features and functions. The first one is associated with the intrinsic nature and physical constraints of power electronics devices and systems. A regular power converter has no internal energy storage capability and its output power capability is limited by the source and the source's availability. Unlike synchronous generators, it lacks mechanical inertia. Other constraints include limited current and voltage withstanding and overloading as well as short-circuit current capabilities. Mitigation measures can be taken by incorporating additional energy buffer or storage components, emulating mechanical inertia, oversizing semiconductor devices, controlling short-circuit current, etc. at the discretion of economics.

The second challenge is linked to the decentralized control scenario, which poses challenge to achieve system stability and global performance, e.g. certain control goals, e.g. dispatching generation economically, maintaining a stable system frequency in a microgrid, or restoring / black starting a power system with a large number of distributed inverters, are at system level and require collective efforts from all the inverters. In this situation, local information may not be sufficient and cooperative with neighboring smart inverters or hierarchical control architecture is necessary to provide an optimal and safe solution.

Multi-inverter, inverter-synchronous generator, or inverter-grid dynamics and transient stability are among the challenges for smart inverter control design. Due to the phenomenon of negative incremental impedance and the interactions of the inverter output filters with line impedance, system instability can be led across various frequency ranges from subharmonics (a few hertz) to superharmonics (a few hundred hertz). Various active damping approaches, output impedance reshaping, and passivity-based control design methods have been proposed to address specific concerns. Further efforts focus on systematic analysis on the stability of complete power electronics-based power systems.

4.2. Trends

It is foreseen that future smart inverter will be more universal and autonomous. The universal trend is in the context of functionality and application. With more and more standardized functions, a smart inverter can be deployed to different applications either as a whole or as a

power electronics building block. Multi-functionalities are realized more and more by new control algorithms to adapt to a dynamical environment, rather than traditional hardware-based approaches though still necessary for certain functions.

In terms of autonomous operation in a decentralized control paradigm, various distributed control techniques such as adaptive droop control [17], self-synchronized control structure [18], etc. will be developed as focused technology. In case of communications available, networked control systems, multi-agent systems, and consensus algorithms [16] can enable smart inverters to utilize the information from their neighbors to accomplish a collective goal with multiple inverters. With these two trends, both hardware modularity and control modularity in a smart inverter can be achieved to qualify for an integral power electronics building block.

Other trends include modular internal structure for better availability and fault tolerance, smart inverters with integrated protective functions without using external circuit breakers to interrupt the fault current at much earlier and smaller magnitude, and so on.

5. Conclusions

This paper reviews the state-of-the-art smart inverter development and proposes a holonic approach to define a smart inverter with the goal to achieve autonomous, adaptive, cooperative, and plug-and-play operation in a decentralized environment such as distributed energy resources or drives.

Smart inverters will find themselves widely in utility applications with high-penetration renewable energy, due to the needs of utility control, grid support and ancillary service requirements, and distributed generations in a microgrid, where likely without any centralized generators, smart inverters can handle complex grid dynamics and uncertainties and adapt to appropriate control modes. Furthermore, with the dawn of Industry 4.0 in manufacturing and production, smart inverters at the machine and sensor levels can contribute to this revolution in industrial power-to-motion applications thanks to their modular, distributed structures and aforementioned smart features.

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