

IFAC WC2014 Tutorial Proposal on Control of Power Inverters for the Smart Grid

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Introduction

Energy and sustainability are now on the top agenda of many governments. Smart grids have become one of the main enablers to address energy and sustainability issues. Renewable energy, distributed generation, hybrid electrical vehicles, more-electric aircraft, all-electric ships, smart grids etc will become more and more popular. Arguably, the integration of renewable and distributed energy sources, energy storage and demand-side resources into smart grids, often via inverters, is the largest “new frontier” for smart grid advancements. Control and power electronics are the two key enabling technologies for this, where power electronics is becoming part of the grid and control is where the “smart” is from. Together with the power systems infrastructure, they form the backbone for smart grids.

An inverter converts DC electricity from sources such as batteries, solar panels, or fuel cells to AC electricity. Inverters are the interface to integrate renewable energy and distributed generation into smart grids. Inverters are also widely used in uninterruptible power supplies (UPS), induction heating, high-voltage DC (HVDC) transmission, variable-frequency drives, electric vehicle (EV) drives, air conditioning, vehicle-to-grid (V2G) etc. Hence, how to control inverters lies at the heart of many energy-related industrial applications. There are several important control problems associated with inverters. For example, how to make sure that the total harmonic distortion (THD) of the inverter voltage and current remains within certain range when the loads are nonlinear and the grid voltage, if present, is distorted; how to make sure that a balanced neutral line is provided for applications where a neutral line is needed, e.g. when three-phase loads are not balanced; how to make sure that inverters can be operated in grid-connected mode or standalone mode and how to minimise the transient dynamics when the operation mode is changed; how to synchronise inverters with the grid so that they can be connected to the grid when needed; how to share loads proportionally according to their power ratings when inverters are operated in parallel; how to connect inverters to the grid in a grid-friendly manner so that the impact on the grid is minimised etc.

Based on the research monograph *Control of Power Inverters in Renewable Energy and Smart Grid Integration* [1] recently published by Wiley-IEEE Press¹, this tutorial will present a systematic treatment of the above problems, focusing on advanced control strategies that have been verified with extensive experiments. The tutorial is divided into four parts: power quality issues, power flow control, parallel operation of inverters and synchronisation. Many innovative concepts, such as synchronverters (inverters that mimic synchronous generators) [2], C-inverters (inverters with capacitive output impedances) [3], robust droop control to share real power and reactive power accurately among parallel-operated inverters without communication [4], harmonic droop control to inject harmonics into the inverter to reduce harmonics in the output voltage [5], and sinusoid-locked loops for synchronisation [6] etc, will be presented in detail. Because of the large amount of experimental results to be presented, this tutorial will interest many major industrial players in renewable energy, energy conversion, energy recovery and storage, smart grid integration, electric vehicles, UPS, aircraft power systems, ship power systems etc.

¹<http://wiley.com/WileyCDA/WileyTitle/productCd-0470667095.html>.

Target Audience

More and more control engineers are, and will be, moving into this area. This tutorial is timely and will attract researchers to explore the challenging problems in this area and fully appreciate the beauty of the integration of control and power electronics. Most of the artful control strategies to be presented at the tutorial will be demonstrated with experimental results and, hence, the tutorial will also attract many practitioners in this area to see how advanced control strategies could improve system performance. The tutorial also provides an excellent opportunity for PhD students and postdoctoral fellows who work in the area to get familiar with the latest developments.

This tutorial is developed based on the successful workshops organised at the 2012 ACC in Montreal, Canada, the 2012 IEEE CDC in Hawaii and the 2013 ACC in Washington, DC, which attracted many participants from academia and industry. From the feedback received according to the questionnaire, the tutorial was interesting, well organised, well prepared and full of latest developments. A similar event was organised at IECON 2012 in October in Montreal, Canada, which was the most popular tutorial at IECON 2012, with all the 100 seats on offer taken well before the registration deadline. Hence, it is expected that this tutorial will attract a lot of participants.

The Instructor

Qing-Chang Zhong is the Chair Professor in Control and Systems Engineering at the Department of Automatic Control and Systems Engineering, The University of Sheffield, UK. He is a Distinguished Lecturer appointed by the IEEE Power Electronics Society for 2014 and 2015. In 2012-2013, he spent a six-month sabbatical at the Cymer Center for Control Systems and Dynamics (CCSD), University of California, San Diego, USA and an eight-month sabbatical at the Center for Power Electronics Systems (CPES), Virginia Tech, Blacksburg, USA. He received his PhD degree in control and power engineering (awarded the Best Doctoral Thesis Prize) from Imperial College London, London, UK, in 2004. He worked at Hunan Institute of Engineering, Xiangtan, China; Technion–Israel Institute of Technology, Haifa, Israel; Imperial College London, London, UK; University of Glamorgan, Cardiff, UK; The University of Liverpool, Liverpool, UK; and Loughborough University, Leicestershire, UK. He (co-)authored three research monographs: Control of Power Inverters in Renewable Energy and Smart Grid Integration (Wiley-IEEE Press, 2013), Robust Control of Time-Delay Systems (Springer-Verlag, 2006), Control of Integral Processes with Dead Time (Springer-Verlag, 2010). He, jointly with G. Weiss, invented the synchronverter technology to operate inverters to mimic synchronous generators, which was awarded Highly Commended at the 2009 IET Innovation Awards. He is a Specialist recognised by the State Grid Corporation of China (SGCC), a Fellow of the Institution of Engineering and Technology (IET), a Senior Member of IEEE, the Vice-Chair of IFAC TC 6.3 (Power and Energy Systems) responsible for the Working Group on Power Electronics and was a Senior Research Fellow of the Royal Academy of Engineering/Leverhulme Trust, UK (2009–2010). He serves as an Associate Editor for IEEE Transactions on Power Electronics, IEEE Access and the Conference Editorial Board of the IEEE Control Systems Society. His research focuses on advanced control theory and its applications in various sectors, including power electronics, renewable energy and smart grid integration, electric drives and electric vehicles, robust and H-infinity control, time-delay systems, process control, mechatronics. He has delivered workshops and tutorials at ACC2012, IEEE IECON 2012 and IEEE CDC 2012 and has been invited to give plenary talks at IEEE PEDG 2013, IEEE GreenTech 2014 and CCDC 2014 etc.

Overview of the Tutorial

Grid-friendly integration

The electrical power system is currently undergoing a dramatic change from centralised generation to distributed generation. More and more distributed/renewable energy generators will be connected to the grid via power inverters. In order to minimise the impact of a large number of inverters connected to the grid, the inverters need to be well controlled so that they are grid-friendly. Synchronverters are

inverters that mimic synchronous generators [2]. They are mathematically equivalent to the conventional synchronous generators and can take part in the regulation of power systems. If a synchronverter is connected to the utility grid and is operated as a generator, no difference would be felt from the grid side between the synchronverter and a synchronous generator. Thus, the conventional control algorithms and equipment that have been developed for synchronous generators driven by prime movers (and which have reached a high level of maturity over 100 years) can be applied to synchronverters. The function of real power control, frequency control, reactive control and voltage control can be implemented with one compact controller, having a symmetric structure. The direction of the energy flow between the DC bus and the AC bus in a synchronverter is changed automatically according to the grid frequency, which greatly facilitates the grid connection of renewable energy resources.

In this part of the tutorial, the synchronverter strategy will be described in details, including modelling of synchronous generators, implementation of synchronverter, real power (frequency) and reactive power (voltage) control etc. Then, the self-synchronised synchronverter strategy [7] is presented to remove the dedicated synchronisation unit that had been believed to be a must-have component for grid-tied inverters.

Parallel-operation of inverters

Due to the limited availability of high-current high-voltage power electronic devices, it is inevitable that multiple inverters are needed to be operated in parallel for large-scale utilisation of renewable energy. For example, a 5GW renewable energy installation will need 1000 inverters of 5MW connected in parallel. Parallel-operated inverters could provide plug-and-play system redundancy and high reliability, which becomes more and more important for end users. Moreover, reliable parallel operation of inverters could lead to the mass production of inverters at lower power level, which could significantly reduce the production cost. A large number of inverters, e.g., in the form of static synchronous compensators (STATCOM) and active power filters (APF), may also be connected in close proximity, which are effectively operated in parallel although they are not directly connected in parallel. Hence, the parallel operation of inverters will be very common.

It should not be assumed that inverters could be operated in parallel automatically. Without proper control mechanisms in place, circulating currents may appear and some inverters may be overloaded, which may cause damage. The system may even become unstable and lead to unwanted behaviours. The parallel operation of inverters has been a major problem in industry. A robust droop controller will be presented so that parallel-operated inverters can achieve accurate load sharing in proportion to their ratings even if their per-unit output impedances are different and/or the voltage setpoints for the inverters are different. Moreover, the fundamental tradeoff between the sharing accuracy and the capability of voltage regulation is considerably relaxed or eliminated if the load voltage is measured accurately. This strategy has made the parallel operation of multiple inverters into reality.

In this part of the tutorial, the conventional droop control strategy is described in details with the fundamental limitations revealed. Then, a robust droop controller [4] is presented to overcome the fundamental limitations so that the sharing of real power and reactive power can be accurate and the output voltage can be regulated within the desired range.

Synchronisation of inverters

Before an inverter is connected to a power source, e.g. another inverter or the grid, it should be synchronised with the source. That is, it should have the same frequency, the same voltage and the same phase as the source. There are also many other application where the synchronisation with an external signal is often needed. The commonly used synchronisation strategies include the phase-locked-loops (PLL), sinusoid-tracking algorithms etc. The performance of the synchronisation unit is critical for the performance of the inverter because the synchronisation unit should provide the references of the grid frequency, phase and voltage accurately and in a timely manner.

In this part, some conventional synchronisation strategies will be presented at first. Then a synchronisation strategy called sinusoid-locked loops [6], which are based on the operation of synchronous generators, will be presented. It is able to quickly recover the frequency, phase and amplitude of the grid.

Power quality control

One of the major problems associated with inverters is the harmonics in the voltage provided. There are two sources of harmonics: one is from the inverters (e.g. because of the pulse-width-modulation and the switching) and the other is from the loads or the grid. The majority of loads today are nonlinear and generate harmonic currents when a purely sinusoidal voltage supply is provided. These harmonic currents then cause harmonic components in the voltage because of the impedances in the distribution network and, also, inside the voltage source. Harmonics are not desirable because they cause overheating, increased losses, decreased kVA capacity, neutral line overloading, distorted voltage and current waveforms etc. It has become a very serious issue in modern power systems. Hence, stringent industrial regulations have been put into place. The total harmonic distortion (THD) of voltages and currents needs to be maintained low, often below 5%.

This part of the tutorial will cover the degradation mechanisms of the voltage quality and a series of approaches to improve the voltage quality, including designing the output impedance of inverters, in particular to be capacitive[3], bypassing the harmonic load current[8], injecting the right-amount of harmonic voltage into the voltage reference to cancel the harmonic voltage dropped on the output impedance (harmonic droop control) [5] etc.

References

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