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A Comprehensive Survey on Control Strategies of Distributed Generation Power Systems – A Review

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ABSTRACT

The proper control method plays a keyrole to ensure for the integration RES into the DGPSs to achieve the highest system reliability and system efficiency. Many types of control strategies have been investigated with or without phase locked loops (PLLs) under balanced, unbalanced and harmonic conditions in the literature. Unbalanced grid disturbances cause overcurrent and overvoltage. Meanwhile, negative sequences lead to serious oscillations on power, current and voltage signals. The aim of this paper is to provide a comprehensive review on various control strategies and PNS extractors for three-phase in verter interfaced DGPS under balanced and unbalanced grid conditions. A comparative analysis for recent PNS extractors has been carried out to produce the signals required for the RCG.High energy demand, low cost requirements and higher reliability requirements increase the importance of distributed generation power systems (DGPSs). The large capacity DGPSs requires high performance control algorithms and synchronization techniques based positive-negative sequence (PNS) extractors tofulfil system reliability and power quality requirements under not only during normal operating conditions, but also under unbalanced grid conditions. The power quality problems caused by voltage unbalances, voltage sag/swell, voltage fluctuations, phase faults and harmonic distortions have critical influences on control of power converter devices interfaced DGPSs.

Keywords: Control methods, unstable, Renewable energy sources, Distributed generation,

1. INTRODUCTION

Motivation in DG technology

The excessive energy consumption and use of high conventional energy sources, such as petroleum and coal threat our world as dif ferent aspects such as; technical, economic and environmental is sues which causes insecure, inadequate energy source, high prices and environmental damages (J ärventausta, Repo, Rautiainen, & Partanen, 2010; Menniti, Picardi, Pinnarelli, & Sgrò, 2010) . In recent years, the rise in energy prices, geopolitical and political events have been revealed the impact of energy on the economy and human being and also remind us limited energy in nature. Therefore, protection of energy sources is often found at the top of the international policy in Toledo, Oliveira Filho, and Diniz (2010). The DGPS mostly involve a broad range of typically ‘low carbon’ or ‘efficient’ technologies which are small-scale and located closer to the end user by means of comparison of conventional generation. The DG technologies can also provide savings in transmission and distribution (T&D), capacity upgrades and removing costly infrastructure (Allan, Eromenko, Gilmartin, Kockar, & McGregor, 2015) .Jordehi (2016); Khamis, Shareef, Bizkevelci, and Khatib (2013).

The size DGPSs can be classified in following:

• The ratings between 1 and 5 kW are called micro DG.

• The ratings between 5 kW and 5 MW are called small DG.

• The ratings between 5 and 50 MW are called medium DG.

• The ratings between 50 and 300 MW are called large DG.

The DG technologies comprise of solar cells (SC), hydrogen based fuel cells (FC), wind turbines (WT), reciprocating internal combustion engines with generators, hydroelectricity and microturbines. The DG users have different power needs. Computer data centres and hospitals require steady-state, uninterrupted power and high-quality due to the sensitivity of equipment.

The main advantages of DG technologies can be listed in following:

• The DG units reduce T&D costs to be closer to customers.

• Provision of high efficiency and environmental protection.

• Improvements in power quality problems.

• The DG ensures a flexible way to select combinations of cost and reliability.

• The DG power plants need shorter installation times.

• The DG power plants exhibit good efficiencies especially in cogeneration and in combined cycles and investment risk is not so high.

• The DG capacity varies from kW to hundreds MW, making it easier to find smaller generators.

• Reduction in vulnerability to terrorism by using military and humanitarian missions.

• The DG is an emergency supply of power and can make up the deficiency of large power grids stability.

• The DG supplies emergency power support, when an electric power system is failure.

2. LITERATURE REVIEW

Many types of control strategies have been investigated with or without phase locked loops (PLLs) under balanced, unbalanced and harmonic conditions in the literature. Unbalanced grid disturbances cause overcurrent and overvoltage. Meanwhile, negative sequences lead to serious oscillations on power, current and voltage signals A modified dual current control method is proposed for minimizing the oscillating components of the active and reactive powers in the DGPSs under unbalanced conditions (J in & Li, 2016) . In Hu, Zhu, and Dorrell (2013), model predictive con-trol method is proposed for a power electronic device in RES based power generation system.

This control method is used to ensure flexible control of active-reactive power, more stable voltage, fast and robust grid synchronisation. Another control strategy, direct Lyapunov method is reported by Mehrasa, Adabi, Pouresmaeil, Adabi, and Jørgensen (2014) to control and analyse dynamic and steady-state model of grid connected DG system. On the other hand, various researchers have been studied on power grid stability under high penetration of DG sources. The other approach is impact of unbalanced grid conditions on grid connected DGPS. Several studies are presented in synchronous reference frame (SRF) or stationary reference frame (STRF)-based control strategies in order to deal with power quality problems caused by unbalanced grid conditions. ollers (Chatterjee, Mohanty, Kommukuri, & Thakre, 2017) .

Control strategies have also critical impact on power converter interfaced the DGPSs under unbalanced conditions. Positivenegative sequence (PNS) components of power system are significantly important data for the control signals. In particular, negative sequences lead to double frequency oscillations, which reduce life time of power converter and DC link capacitor. The measured reference signals from PLLs based PNS extractors can be used in voltage, current and power controllers to minimize oscillations (ripples) on control signals (Yao, Xiao, & Guerrero, 2015) . Another power problem caused by unbalanced grid conditions is overcurrent phenomenon. The excessive current can damage inverter and affects the system operation reliability. Various flexible control strategies have been developed with PNS based reference current generators (RCGs) to deal with overcurrent and ensure maximum allowable power (Du et al., 2016; Guo et al., 2017;

Therefore, PNS components play key role for correct implementation of the low voltage ride-through (LVRT) and high voltage ride-through (HVRT) capability in grid connected inverter applications under unbalanced grid faults. A number of studies have been fulfilled on PNS extractors based controllers in the literature. Delay signal cancellation (DSC) is proposed by Jin et al. (2017) to extract PNS components for using in control strategies. However, it exhibits slow response time and affected by harmonic omponents. In Chilipi, Al Sayari, Al Hosani, and Beig (2016), third-order sinusoidal signal integrator (TOSSI) based PNS extractor is presented to generate reference current signals.

In Sarıbulut (2016), average filter based PLL (APLL) is an effective technique to extract PNS components and harmonic components. Dual APLL named as DAPLL is improved by (Çelík and Meral, 2019) . The DAPLL, containing two average filters instead of using multiple filters, separates PNS components quickly and accurately. In Tsengenes and Adamidis (2011a), SRF-based active and reactive power controllers are proposed for active power filters to eliminate current harmonics without using PLL in the d–q coordinate transformation system.

the RCG and current limitation control under both balanced and unbalanced conditions compared with previous studies such as Blaabjerg, Teodorescu, Liserre, and Timbus (2006), Bouzid et al. (2015), Parvez, Elias, Rahim, and Osman (2016) and Guerrero Rodríguez, Rey-Boué, Bueno, Ortiz, and Reyes-Archundia (2017). The general structure of RES (SC, WT and FC) based DGPS is shown (M.E. Meral, D. Çelík,2018)Negative sequences cause increasing losses, oscillations on the dc-link, power, voltage and current signals and have also negative effects on equipment such as power electronic converters, induction motors and adjustable speed drives (Rezaei & Soltani, 2015) . The impact of grid disturbances such as unbalanced grid voltage, faults and harmonic conditions on renewable energy sources are given as follows.

2.1. Solar cell

The SC converts the energy of sunlight into direct current electricity (J ordehi, 2016). Solar power generation has become significant sources of the DGPSs. The SC can be used widely for various applications in grid connected systems (Teke, Yıldırım, & Çelík, 2015) .Solar systems are commonly prone to operate near unity power factor. Sag and swell can change rate of reactive power flow in the system. This issue affects power factor.

2.2. Fuel cell

Hydrogen based FCs is one of the most attractive power supply for the DGPSs technologies (Shahnia et al., 2010) . Therefore, proper control algorithms are required to provide frequency regulation, DC bus power regulation and DC bus voltage under balanced and unbalanced conditions. To avoid overloading power converter, current controller limit power that the FC unit can supply to grid under grid disturbances.

Table 1 List of nomenclatures.

Nomenclatures			
DG Distributed generation	**UPS** uninterruptible power supplies	**DB** Dead-beat	**DPC** Direct power control
PLL Phase locked loop	**LPF** Low pass filter	**PNS** Positive and negative sequence	**DSOGI** Dual second-order generalized integrator
DGPS Distributed generation power system	**FACTs** Flexible AC transmission	**HC** Hysteresis control	**PID** Proportional-integral differentiation
MVF Multivariable filter	**EPLL** Enhanced phase-locked-loop	**FCP** Flexible control parameter	**PD** Phase detector
WT Wind turbines	**CPD** custom power devices	**FOPI** Fractional order proportional integral	**PC** Predictive control
MAF Moving average filter	**DSRF** Double synchronous reference	**STRF** Stationary reference frame	**THD** Total harmonic distortion
FC Fuel cell	**T&D** Transmission and distribution	**PR** Proportional resonant	**RC** Repetitive control
MCCF Multi complex coefficient filter	**DDSRF** Decoupled double synchronous reference	SRF Synchoronous reference frame	**VCO** Voltage controlled oscillator
SC Solar cell	**MW** Megawatt	**PI** Proportional integral	**FCP** Flexible control parameter
TOSSI Third order sinusoidal integrator	DSC Delay signal cancelation	**RCG** Reference current generator	**CPD** Custom power device
RES Renewable energy sources	**kW** Kilowatt	**LVRT** Low voltage ride through	
DAPLL Dual average filter PLL	**MAF** Moving average filter	**HVRT** High voltage ride through	

2.3. Wind turbine

The RES technologies such as wind energy are the fastest growing sector. The WT is captured by generator blades before it is converted into mechanical energy to electrical energy (Hasan, Hassan, Majid, & Rahman, 2013) .

3. THE PNS EXTRACTORS AND SYNCHRONIZATION UNITS OF DGPSS

The PLL based PNS extractors are a crucial part of power converters interfaced DGPSs. They are mainly used in RES based DGPSs, dynamic voltage restorers (I˙ nci, Bayindir, & Tumay 2016b) ,trong influence on control of grid tied power converter devices. Therefore, fast and good robustness PNS components should be required to determine control signals of the power converters.

3.1. The traditional PLL

The unbalanced and distorted grid conditions have high influences the power quality of the DGPSs since unbalancing and harmonic distortions lead to power, current and voltage oscillations (ripples) on control signals (Tümay, Meral, & Bayindir, 2009) . n recent years, various advanced PLLs have focused on enhancing the disturbance rejection capability of traditional SRF-PLL and overcome power quality problems in power systems under abnormal conditions although traditional PLL ensures high performance under normal conditions (Li, Wang, Han, Tan, & Guo, 2016b; Lubura, Šoja, Lale, Ristovic´, & Iki c´, 2015),in (Mehmet Emin Meral, Do gˇan Çelík,2018)

3.2. Enhanced PLL based PNS extractor

The traditional PLL gives a good solution for making hardware. In traditional PLL, three phase AC signals are converted into two phase DC signals (dq).For three phase applications, dual EPLL (DEPLL) is eveloped under grid disturbances. The DEPLL employs to extract PNS components. It can be used for eliminating oscillations on power, current and voltage signals. Fig. 3 a shows a small modification with the quadrature output signal Vq α is 90° - lagging V α. The transfer function of EPLL is written in following.

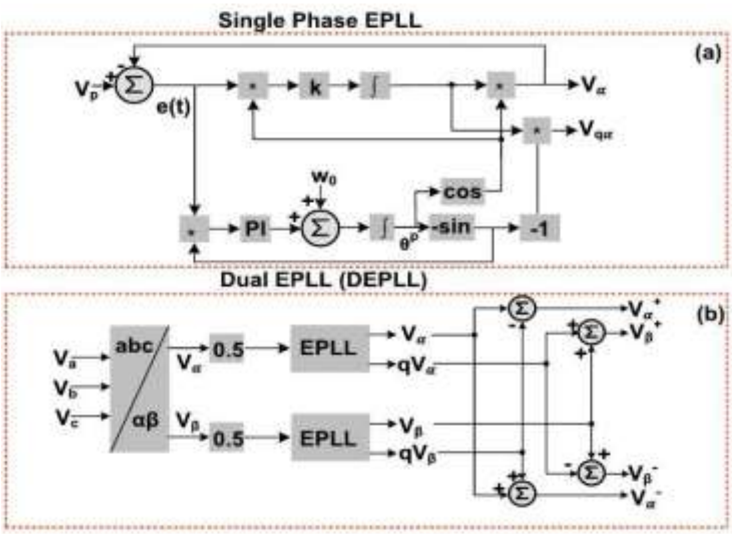

Fig. 1. The using EPLL; (a) for measurements of orthogonal signals and (b) for separation of PNS components.

$$V_a(s)/V_p(s) = \frac{\mathrm{ks}}{s^2+ks+w^2} \quad (1)$$

The PNS voltage components based on STRF and SRF are extracted in (Mehmet Emin Meral, D. Çelík,2018)

$$v^+ = v_d^+ + jv_q^+ \quad (2)$$

$$v^- = v_d^- + jv_q^-$$

Fig. 1 b shows the implementation of EPLL in STRF dimensional instead of SRF (Rodriguez et al., 2006) since;

• Low computational burden due to using only two EPLL

• The DEPLL extracts PNS components

• Provide high robustness due to blocking zero-sequence components in its input.

• Remove the fourth EPLL because of extracting PNS components

The DEPLL can be applied in control of unified power-quality conditioner, FACTs devices, CPD and DGPSs (J aalam, Rahim, Bakar, Tan, & Haidar, 2016) .

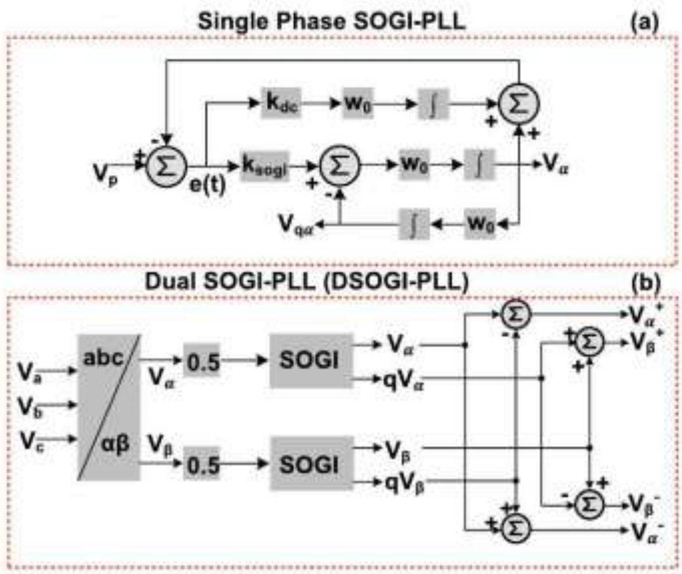

Fig. 2. The using SOGI; (a) for measurements of orthogonal signals and (b) for separation of PNS components.

Dual second order generalized integrator based PNS extractor is shown in Fig. 2. The closed-loop transfer functions of SOGI can be written in (Mehmet Emin Meral, D.

Çelík,2018)

$$\Delta s = s^3 + (k_{sogi} + k_{dc})\mathrm{w}_0 s^2 + w_0^2 s + \mathrm{k}_{dc} w_0^3 \quad (3)$$

where w 0 is fundamental frequency, with DSOGI-PLL create two orthogonal signals V α and Vq α. The signal V α is in phase with input signal V p. The bandwidth of SOGI is affected by G 1 (s) and G(s) transfer functions. The selection of ks ogi and k dc (DC offset) parameters can affect error signal and dynamic response of PLL. The measured PNS components from DSOGI-PLL can be used to obtain RCG.
Then performance comparisons of PNS extractors (M.E. Meral, D. Çelík,2018) shown in Table 2.

Table 2 performance comparisons of PNS extractors

PNS extractors	Advantages	Drawbacks
DEPLL	• Ensure fast dynamic response. • Very good ripple filtering. • Provide higher robustness.	• More computation burden when compared with MVF-PLL. • Affected by harmonic components
DSOGI	• Provide fast dynamic response. • Very good ripple filtering.	• Longer settling time and more oscillations on signals, in comparison with DEPLL. • More complicated than other PLLs (Yang et al., 2015) .
MVF	• Easy implementation. • Low computation burden.	• Longer setting time. • More oscillations.
MAF	• Provide fast dynamic response. • Very good ripple filtering.	• Cannot cope with interhamonics.
DDSRF	• Unbalanced grid faults have no steady-state negative effect. • Easier tuning for control parameters (L una et al., 2015) .	• Cause to a time delay. • The presence of harmonics may cause oscillation on control signals. • High computation burden.
MCCF	• Provide fast dynamic response. • Provide a solution for low and high order harmonics.	• More computation burden. • Contain more sub-modules.

4. DEAD BEAT CONTROL

Many researchers have been investigated dead-beat (DB) control of three phase inverter. Fast voltage and current regulation are very important to mitigate disturbances in control of three phase inverter interfaced DGPSs. The DB control is one of the predictive controllers and it is used to eliminate the forecast error so that the reference current can be tracked correctly without any error. control methodes according to (M.E. Meral, D. Çelík,2018) shown in Table 3

Table 3 Advantages and drawbacks of voltage and current regulation controllers.

Control methods	Advantages	Drawbacks
Dead-beat control	• Very effective way to ensure fast load voltage regulation. • Mitigation of voltage disturbances in power/current controller. • Provides high dynamic and fast response for microprocessor. • Used to eliminate the forecast error.	• Need a robust filter. • Implementation in high frequency microcontroller (Arulkumar et al., 2016)
Predictive control	• Provides more precise current control with low harmonics. • Minimized the forecast error. • Reduce switching frequency for high-power converter devices. • Deals with nonlinearities.	• Requires a filter. • Has more computation burden. • Sensitive to parameters changes. • Its applicable is difficult.
Hysteresis control	• Has simple structure. • Provides a high dynamics. • Independent of load parameters • Good robustness • Ensure high system stability	• Switching the frequency variation with load parameters and operating conditions, these cause to resonance problems • Application of HC is limited by switching losses. • Current tracking errors cannot be limited.
Repetitive control	• For grid disturbances, provides robust performance.	• Not deal with

	• Ensures a zero steady-state error at low and high order harmonics. • Provide good performance with frequency variations.	load disturbances. • Exhibits slow response time under fluctuating loads.
Direct power control	• Has a simple control structure. • Has fast dynamic response. • Affected by the parametric variations. • Has high THD, caused by nonlinear loads.	• Has losses of the converter caused by non-constant switching frequency. • Design the switching noise filters.
PI based controller	• Ensures simple and easy implementation. • Applicable to both single-phase and three-phase systems in SRF..	• Cannot track the sinusoidal reference signal under nonlinear load variation.
PR based controller	• Provide fast dynamic response. • Overcome stability problems. • Provide robust current reference frame for current controller. • Low computational burden, compared with PI controller. • Applicable to both single-phase and three-phase systems in STRF	• Sensitive to frequency variations. • More complexity than hysteresis and dead beat controller (Arulkumar et al., 2016) . • It is difficult to implement in reality. • The infinite gain causes an infinite quality factor.
Fractional order controller	• Implemented with various control methods such as PI, PID fuzzy ic controller, unified power flow controller and sliding mode control • Provides fast .dynamical response, more stable, good robustness and flexibility. • Robustness to high frequency noise (Ahn et al., 2009) .	• It is not easy design controller, compared with PI and PID controller (Ahn et al., 2009) . • Less sensitive to variation of control parameters.
Dual Current Controller	• Ensure good performances under unbalanced conditions. • Easily affected by high order harmonics.	• Has more computational burden.

5. DISCUSSION ON COMPARISON OF CONTROL STRATEGIES

As shown in Table 4, a comparative analysis has been performed to better evaluate performances of various control strategies. The control strategies are discussed and evaluated in terms of current regulation control, regulation of active and reactive power, PNS extractors, controllability of active and reactive power oscillations, and number of FCP.

Table 4 Comparison of control strategies performance.

Control strategy	Regulation of P, Q	Control of P, Q oscillations	Current limitation	Number of FCP	Current regulation	PNS extractors
(Song & Nam, 1999)	P	only P	No	No	DSRF-PI	SRF-PLL
(Rodriguez et al., 2007a)	P	No	No	No	DB	DSOGI-PLL
(Alepuz et al., 2009)	P, Q	Yes	No	No	LQR	DSC-PLL
(Wang et al., 2010)	P, Q	Yes	No	1	PR	MVF-PLL
(Reyes et al., 2012)	P, Q	No	No	No	DDSRF-PI	DSRF-PLL
(Du et al., 2016)	P, Q	Yes	Yes	2	PR	DSOGI-PLL
(Kabiri et al., 2016)	P, Q	Yes	No	1	DSRF-PI	DSOGI-PLL
(Sosa et al., 2016)	P, Q	only P	Yes	2	PR	DSOGI-PLL
(Sun et al., 2016b)	P, Q	Yes	No	2	PR	DSOGI-PLL
(Guo et al., 2017)	P, Q	Yes	Yes	2	PR	MCCF-PLL
(J in et al., 2017)	P, Q	No	No	No	DSRF-PI	DSC-PLL
(Al-Shetwi et al., 2018)	No	No	Yes	No	SRF-PI	SRF-PLL
(Huka et al., 2018)	No	No	Yes	No	SRF-PI	SRF-PLL
(L ópez et al., 2018)	P, Q	only P	Yes	2	PR	DSOGI-PLL
(T odorovic´ et al., 2018)	P, Q	Yes	Yes	No	PR	DSOGI-PLL
(Çelík & Meral, 2019)	P, Q	Yes	Yes	1	FOPI	DAPLL

6. CONCLUSION AND RECOMMENDATIONS

The control methods play a significant key role on three phase inverter interfaced DGPSs. In recent research studies, novel control strategies with PNS extractors are developed to remove oscillations on power, current and voltage signals. In this paper, a comprehensive review on various control strategies and synchronization tech niques based PNS extractors for interlinking three phase inverter in DGPSs are performed and surveyed under balanced and unbalanced grid conditions. The advantages and drawbacks of the control strategies and the PNS extractors have been investigated and evaluated. Generally, DEPLL, DSOGI, MVF and MCCF based PNS extractors can be used more in STRF based controllers and MAF and DDSRF based PNS extractors can be used more in SRF based controllers. The various current and voltage regulation controllers have also been reviewed and compared to accomplish a fast dynamic response and minimization of steady state tracking error. The PNS extractors are used to obtain the RCG for use in conventional and flexible control strategies under unbalanced and armonic conditions. The theoretical and comparative analyses of conventional and advanced flexible RCG based control strategies are comprehensively evaluated and reviewed. Overcurrent phenomenon is also discussed at power converter capacity. Another advanced control strategy is presented without any using PLL for researchers studying on synchronization methods. Comparative analyses have been performed to evaluate better performances of PNS extractors and control strategies in Tables 2, 3 and 4. This paper is also comprehensively reviewed that will be helped researchers, users, and suppliers of the electrical power system to get an overview for future research and studies. The future research directions based on the discussions in this study are suggested in following:

• The selected a proper PNS extractor with control strategy can be applied to the power conversion based applications such as DGPS, FACTs devices, CPD including dynamic voltage restorer, series shunt filter, static transfer switch, UPS under balanced and unbalanced grid conditions

• The power grid stability can be studied under high penetration of DG sources.

• The flexible control strategies can be studied to meet LVRT and HVRT requirements demand DG power plants.

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