ENHANCED PHASE-LOCKED LOOP STRUCTURES FOR POWER AND ENERGY APPLICATIONS

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To my parents, family and teachers

BRIEF CONTENTS

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PREFACE

Phase-locked loop (PLL) is extensively used in power systems and power electronics for the purposes of synchronization, control, and signal detection and estimation. The significance of the PLL constantly grows with the proliferation of new devices that operate in connection with the utility grid. Restructuring of the power system has widely encouraged the interconnection of distributed generation and storage units to the grid using power electronic interfaces. Generators based on renewable energies such as solar and wind, are increasingly developed and used at low and medium voltage levels. The concept of microgrid to encompass a number of generating, storing, and consuming entities that can operate in both grid-connected and stand-alone modes has become a realizable technology. Digitization of power system and usage of state-of-the-art communication and computer technologies to increase power system reliability and efficiency has brought about the idea of the smart grid. The PLL is a pivotal component of such technologies. The single-phase PLL (which was seldom needed in the traditional power system) is now crucially needed for controlled operation of a single-phase active distribution system and a single-phase microgrid. While having a simple and robust structure for implementations in digital platforms, the PLL provides a stable and accurate reference for synchronization despite the system oscillations and distortions. Another application area of the PLL is in uninterruptible power supply systems. The PLL can also be a competent algorithm for wide area measurement, protection, and control using synchronized phasors. The ability of the PLL to track frequency swings closely and to provide an accurate estimate of signals and parameters makes it highly desirable. The PLL is also capable of measuring power quality phenomena and indices and can be used in the realization of smart meters and similar applications in a smart grid.

Despite the long history of the PLL and many books written on its applications in various engineering fields, there is no single independent book dedicated to the PLL structures suitable for power system and power electronics applications. With the major ongoing restructuring in the power system and the proliferation of new devices, such a book would be of immediate need and significance.

The text presented here summarizes the experiences of the author gained from working with different PLL structures over the past two decades. The text is particularly written for power engineering applications and only discusses the major PLL structures that are directly applicable and are interesting for such applications. It is written in a simple language in order to make it accessible to a wide audience. Specifically, complicated mathematical proofs are avoided. However, the basic analysis that helps understanding and further developments is provided for each structure.

Although many applications are sporadically mentioned in the text, there is no focus on any specific application. This provides a more general outlook to the book, allowing a variety of readers to benefit from it. The application of grid-tie inverters is dealt with in detail due to the growing interest in this technology. The book is primarily intended for graduate students, application engineers, and researchers who work in related areas. It may also be considered as a textbook for an advanced special topic course at the graduate level.

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M. K. G.

ACRONYMS

1ϕ, 3ϕ	single phase, three phase
3EPLL	three-phase EPLL
AC	alternating current
ANF	adaptive notch filter
APF	all-pass filter
BPF	band-pass filter
BSF	band-stop filter
dB	decibel
DC	direct current
DCM	droop control method
DF	direct form
EPLL	enhanced phase-locked loop
FIR	finite impulse response
FLL	frequency-locked loop
FVT	final value theorem
GC	grid-connected
GCC	grid-connected converter
GF-EPLL	generalized filtering EPLL
Hz	Hertz
I	integrating
IEEE	Institute for Electrical and Electronic Engineers
IIR	infinite impulse response
ISC	integrated synchronization and control
LF	loop filter
LPF	low-pass filter
LQR	linear quadratic regulation
LQT	linear quadratic tracking
LTI	linear time invariant
MDCM	modified droop control method
MPPT	maximum power point tracking
OL-EPLL	open-loop EPLL

P	proportional
PD	phase detector
PI	proportional-integrating
PL	pseudolinear
PLL	phase-locked loop
PR	proportional-resonant
PV	photovoltaic
R	resonant
s	second (unit of time)
SA	stand-alone
SG	synchronous generator
SOGI	second-order generalized integrator
SRF	synchronous reference frame
THD	total harmonic distortion
Trig	trigonometric function
UPS	uninterruptible power supply
VCO	voltage-controlled oscillator
W-EPLL	windowed-EPLL

SYMBOLS

$u(t)$	input signal
$y(t)$	output signal
$e(t)$	error signal: $e = u - y$
H	Hessian matrix
ϕ_i	total phase angle of input signal
ϕ_o	total phase angle of output signal
ω_i	frequency of input signal
ω_o	frequency of output signal
U_i	amplitude of input signal
U_o	amplitude of output signal
δ_i	initial phase angle of input signal
δ_o	initial phase angle of output signal
$\Delta\omega_i$	deviation of input frequency from nominal value $(\omega_i - \omega_n)$
$\Delta\omega_o$	deviation of output frequency from nominal value $(\omega_o - \omega_n)$
$\Delta\phi_i$	deviation of input phase angle from nominal value $(\phi_i - \omega_n t)$
$\Delta\phi_o$	deviation of output phase angle from nominal value $(\phi_o - \omega_n t)$
s	Laplace domain variable; unity magnitude synchronizing signal
t	time variable
z	Z-domain variable
ω_n	nominal value of system frequency
ξ	damping ratio of a second-order linear filter
$\perp$	90° phase delay: $(\cos\phi)^{\perp} = \sin\phi$, $(\sin\phi)^{\perp} = -\cos\phi$
$\circ$	degree (deg)
μ	EPLL gains
$\dot{x}$	$\frac{d}{dt}x$ (time derivative)
J	cost function
θ	vector of parameters
$\frac{\partial}{\partial\theta}J$	partial derivative
∇	gradient operator
$\otimes$	cross product: $x \otimes y = x_1 y_2 - x_2 y_1$
I_2	2×2 identity matrix

$v_g(t)$	grid voltage
$i(t)$	inverter current
L	inductance
C	capacitance
P	real power
Q	reactive power
$p(t)$	instantaneous real power
$q(t)$	instantaneous reactive power

INTRODUCTION

WHY IS A PHASE-LOCKED LOOP DESIRED IN POWER ENGINEERING?

In an alternating current (AC) power system, phase angle is an important piece of information. At the global system level, synchronized phasors provide fundamental information for the analysis of the whole system. At a more local level, the phase angle information is crucial for efficient interaction of different equipment with the electric utility grid. Power electronic converters, for instance, are used to interface distributed generators with the grid. The control algorithms within such converters that control turnon/turnoff operation of power electronic switches require accurate phase angle information to ensure synchronized and desirable operation.

Signals in an AC power system are ideally sinusoidal at a single frequency ω_n. In practice, however, there are two main deviations from this ideal case, which are explained as follows:

1. Signal distortions in the form of bias, harmonics, interharmonics, transient disturbances, notches, and noise exist. The distortions are mainly caused by nonlinearities in the system components.
2. The frequency is not exactly at ω_n due to ever changing generation–consumption conditions of the whole power system.

Linear filters can be used to attenuate distortions and noise and to overcome the first problem. A filter, however and due to the second problem, distorts the phase angle information of interest, and such distortion can be compensated only if the frequency is known accurately. A phase-locked loop (PLL), benefiting from some nonlinear operations, while having a very simple and robust structure, overcomes both problems simultaneously: it detects the phase angle in a low-pass loop that attenuates distortions, and moreover, it does not introduce any shift or distortion to the phase angle despite frequency variations.

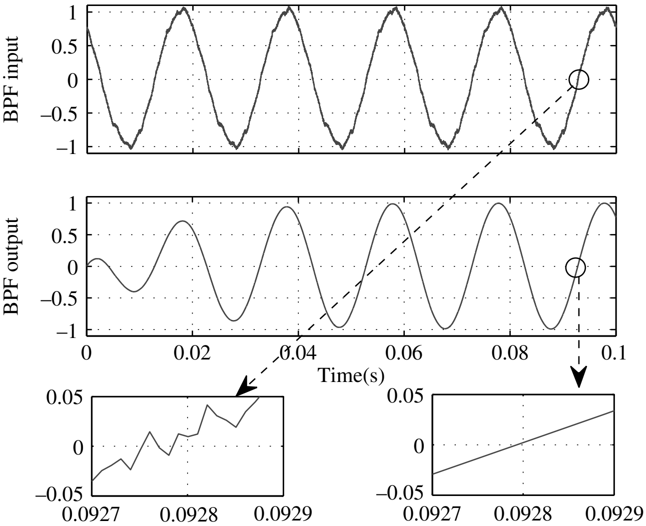

FIGURE I.1 A power system signal before and after applying to a band-pass filter.

In order to shed more light on this issue, consider an example of a 50-Hz power system signal shown on top of Figure I.1. This signal, representative of a typical grid voltage signal, has a small amount of low-frequency and high-frequency harmonics and some white noise. The total harmonic distortion (THD) for this waveform is about 5%. Due to distortions and noise, multiple zero crossings may occur. If this signal is passed through a second-order band-pass filter (BPF) with transfer function

$$H_{\mathrm{BPF}}(s) = \frac{2\xi\omega_n s}{s^2 + 2\xi\omega_n s + \omega_n^2}, \tag{I.1}$$

the output signal shown on the bottom of Figure I.1 is obtained. This signal is much smoother with a THD of about 1%. The values of $\xi = 0.25$ and $\omega_n = 2\pi 50$ are used, and the settling time of filter transients is about two cycles with a time constant of about a quarter of a signal cycle. The phase angle information can be derived from the output signal provided that any possible BPF effect is compensated.

Now, let us study possible impacts of the BPF on phase information. The frequency response of the BPF with $\xi = 0.25$ and $\omega_n = 2\pi 50$ is shown in Figure I.2 for a large range of frequencies and then its zoomed version over a 2 Hz range around the center frequency. It shows that the filter attenuates low-frequency and high-frequency components. Specifically, the direct current (DC) component is completely blocked by this filter. The fifth harmonic,

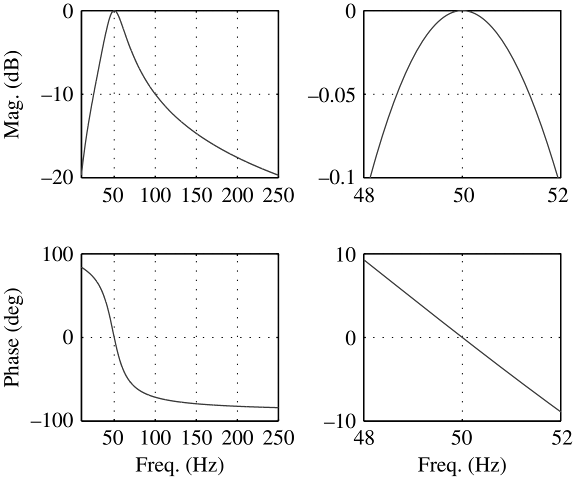

FIGURE I.2 Frequency response of the second-order band-pass filter.

for example, is attenuated about 10 times (or −20 dB). The BPF does not introduce any distortion at its center frequency. However, a phase-shift as large as nearly 10° can happen if the frequency of the input signal is allowed to change ±2 Hz, see Figure I.2. The phase shift can be as large as 2° for a frequency uncertainty of ±0.5 Hz. A frequency uncertainty of ±0.5 Hz is not unexpected in most power systems while even larger values are expected during transients or in smaller/weaker grids [7]. The IEEE standard on synchrophasors, for example, requires an accuracy where the phase angle error does not exceed 0.5° for a frequency range of ±5 Hz [10].

An amount of 2° of phase shift translates to about 100 μs for a 50-Hz system. This amount of phase shift is not admissible for critical grid-connected applications. A time shift of 100 μs is equal to one full switching period for a power electronics converter with a switching frequency of 10 kHz. When the signal is used within a control loop, the delay reduces the system stability margins and might even cause instability for a control loop with high bandwidth.

A desired solution would be a mechanism that can offer filtering of undesired effects and adaptivity to system frequency. The PLL satisfies the two conditions with the simplest structure possible. The PLL, in its multiple forms, is widely used for numerous applications in power engineering, thanks to its frequency adaptivity, noise attenuation, robust properties, as well as other features that are desirable for specific applications. This text is intended to offer a comprehensive, yet simple to understand, treatment of the PLL in the context of power engineering applications.