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A novel approach for hybrid system simulation and design based on an enhanced load flow calculation methodology

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Abstract

This article presents a modified method of performing power flow calculations as an alternative to pure energy-based simulations of off-grid hybrid systems. The enhancement consists in transforming the scenario-based power flow method into a discrete time-dependent algorithm with the inclusion of bus and controller dynamics. The output of the simulation can be then used to run economic calculations as well as for the evaluation of the technical feasibility of a given network configuration.

Keywords. Power system simulation, hybrid systems, renewable energy integration, off-grid systems.

1. Introduction

Due to the steady decrease in photovoltaic (PV) and storage investment costs, off-grid hybrid systems have become quite popular in the last decade to offset the increasing variable costs of diesel generator sets (gensets) while reducing CO_2 emissions at the same time.

The economic feasibility of these systems, however, depends greatly on the size of the system, the PV proportion, the capacity of the storage system (if any) and on the performance of the control system [1], [2].

While available simulation tools such as Homer Energy provide great insights and allow optimization on the component sizes as stated by [3], they are based on energy flows [4], which run on the assumption that the system is running as long as the energy provision is equal to the energy consumption, disregarding line loading and potential frequency or voltage variation problems.

Load flow analyses, on the other hand, address these matters but typically require a very detailed topology and are not suitable for economic calculations. Leading power systems planning software partially addresses these shortcomings, introducing the so called quasi-dynamic simulation.

This paper proposes a set of enhancements to the traditional power flow method in order to make it suitable for both use cases: Economic sizing and simple grid stability.

2. Traditional power flow calculation

"Power flow studies are of great importance in planning and designing the future expansion of power systems, as well as in determining the best operation of existing systems." [5]

A power flow[1] study of a given system with N buses solves for the voltage magnitude $\mid V_i \mid$ and angle δ_i for each of the nodes $i \in [1, N]$ in the system, also called buses, while maintaining the constraints of the scheduled powers P_i and Q_i. It also provides a solution for the currents flowing through each of the lines connecting these buses [5].

The method defines three basic types of buses, which emulate the actual behavior in traditional power systems. These types are:

Slack bus: Used to emulate an overlaid grid. This is used as reference and sets the magnitude and angle of the voltage at the bus. This is typically regarded as the first bus (V_1). The method computes the power import/export to/from the system.

Voltage controlled or PV bus: It emulates a traditional generator with voltage control, which injects a certain scheduled power. In this case, only the phasor magnitude and the scheduled power are known.

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[1] Often also found in the literature as *Load flow*

Load or PQ bus: This bus emulates typical loads. For these buses both magnitude and phase of the voltage is unknown but active/reactive power consumption/production is set.

Table I shows a summary of the traditional power flow problem having N buses, N_g of which are generation buses (PV-Buses), N_l load (PQ) buses and exactly one Slack bus.

Table I. – Summary of the power flow problem

Bus type	**No. of Buses**	**Quantities specified**	**Unknown quantities**
Slack ($i = 1$)	1	$\delta_i, \mid V_i \mid$	0
Voltage controlled (PV Bus)	N_g	$P_i, \mid V_i \mid$	δ_i, Q_i
Load (PQ Bus)	N_l	P_i, Q_i	$\mid V_i \mid, \delta_i$

Since the nature of the equations is non-linear, a numerical method is used. One of the most used methods is the *Gauss-Seidel iterative method*.

A. Limitations of the traditional power flow method

The traditional power flow method is a great method for planning and designing a power system based on possible *scenarios*. This method has however its limitations if it is to simulate dynamic systems like off-grid hybrid systems. The most important ones are:

- It lacks the possibility of simulating a time series of generation and load profiles.
- It does not integrate the behavior of grid control mechanisms and only integrates generation voltage regulation controls in a stationary way.
- It does not consider the impact of a given configuration on the system's frequency.

The shortcomings of the traditional power flow method may be better explained if one considers the typical use case for system simulations. Figure 1 shows the typical load and generation profile for a simple PV-diesel hybrid system with a PV installed power of around 25% of the genset power.

The depicted hourly load profile present different diesel generator power injection, which is in charge of maintaining active power equilibrium. Each of these calculated demands pose a different power flow scenario, which may or may not impact frequency or lead to voltage issues or line overloading.

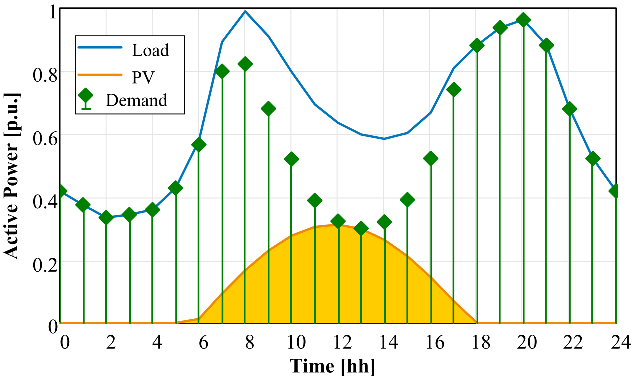

Fig. 1. Typical hourly load profile for off-grid PV-Diesel systems

3. The enhanced power flow method

To overcome these shortcomings a new method is proposed, in which the active and reactive power injection of a given bus are defined as a function of generator scheduled power (generation profile) as well as also on generator controls, which in turn are also dependent on the system frequency f_{sys}. A similar approach is implemented in leading power system simulation software and known as quasi-dynamic analysis [6], however this does not include frequency dependency, which can greatly affect system performance on site.

Introducing a frequency dependency impacts several parameters of the power flow problem. On the problem description side, frequency impacts the line impedance and thus the calculation of the bus admittance matrix Y_{bus}, which in turn affects the line loading and power distribution. On the operational side, frequency dependency describes the reaction of generators as now typically required in most grid codes.

Since the enhanced power flow method is independent on the simulation time step T_s, the dynamic response may be anything from a static droop characteristic (for $T_s > 60\,s$) to even the dynamic response of generator's inertia ($T_s < 1s$), therefore generator controls must have a model able to cope with the different time steps. Figure 2 shows the typical characteristic of a generator running in droop mode.

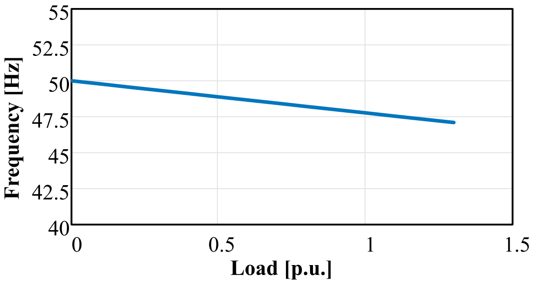

Fig. 2. Typical droop characteristic of generators (5%) if not working in isochronous mode

A. Methodology

The proposed method can be applied to generate a time series of bus powers, line currents and bus voltages for a given time period meaning K_{steps} steps. An overview is presented in Figure 3. The method can be briefly described with the following steps:

1. Preparation of the problem set:
    (a) Setting bus configurations.
    (b) Creation of line and shunt admittance for each line/bus.
    (c) Creation of profiles (time series) for load and non-dispatchable generation sources.

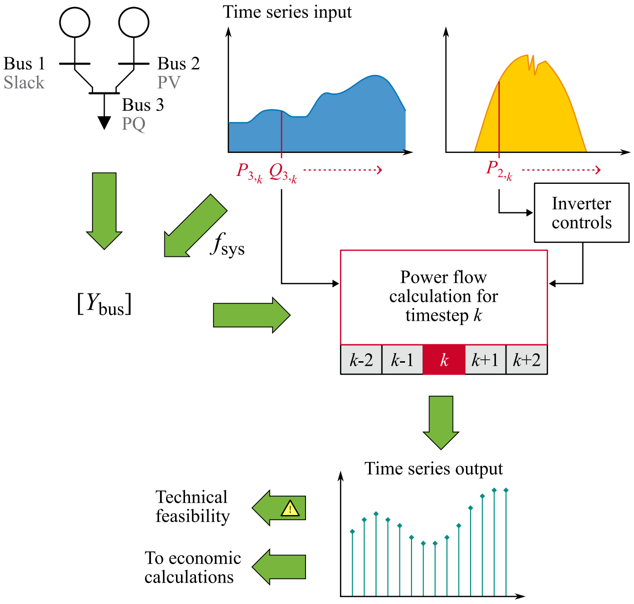

Fig. 3. The enhanced low-flow method at a glance

2. Solution of the initial power flow ($k = 0$), assuming all unknown bus voltages are set to $1\angle 0°$ p.u. and ideal characteristics of generators and loads (i.e. using traditional power flow method). f_{sys} is assumed to be the nominal frequency.
3. Solve for each of the next time steps ($k = 1 \dots K_{\mathrm{steps}}$)
    - (a) Assume state variables (bus voltages) are equal to their values at the previous step ($V_{i,k,0} = V_{i,k-1}$).
    - (b) Calculate the scheduled active power of each node P_i by numerically solving the active power balancing set of equations with previous frequency as initial value ($f_{\mathrm{sys},k,0} = f_{\mathrm{sys},k-1}$) and considering generator controls.
    - (c) Applying the new frequency to admittance of lines and buses.
    - (d) Calculation of a specific admittance matrix $[Y_{\mathrm{bus}}]$.
    - (e) Solution of power flow for time step k, obtaining the new voltages, currents and bus powers.
    - (f) (Optional) verification that voltages, currents, powers and frequency are within the acceptable limits (set by the scenario) and taking necessary actions, like issue a warning or even emulate protections.

B. *Solution for different step times*

The solution explained in point 3(b) requires knowledge of the dynamics of the generator and its controls. This can be especially challenging since there are different simulation time steps for different applications. In order to facilitate the use of one source model for different applications and time frames, the dynamics can be described in terms of the discretized transfer functions with explicit calculation of the factors based on the time step as described by [7].

With this approach, it is possible to address the different precision requirements with only one model. A reference implementation for a diesel generator is presented in Section 5.

C. *Advantages over energy-based simulations*

The proposed method offers the following advantages over pure energy-based simulations:

- It provides information on the technical feasibility of the configuration.
- It gives a better overview on the loading of lines and/or generators.
- It gives an overview on potential voltage and/or frequency contingencies.
- It allows for simulating real control systems.
- It allows simulating coarse time steps for economic calculations as well as fine time steps for scenario/congestion management.

4. Implementation

The enhanced power flow method is to be at the core of a new simulation platform for the simple evaluation of hybrid projects all around the world. This open source initiative (at its very initial stadium) is based on the Java platform and will provide enhanced insights of the power system as well as providing data for economic decisions.

The implementation of the main enhanced power flow algorithm in Java is still under development but has been described and tested in MathCAD®. The genset controls have been already implemented in Java.

5. Validation

In order to assess the expediency and efficiency of the method proposed, the simulation was run for a network, shown in Figure 4. It is based on a system proposed by [5]

The system comprises four buses (nodes). The first one is designated as slack bus, it is a node with the diesel generator, which is a main power source for the system. Buses 2 and 3 are load buses, bus 4 has a PV-generator, so it is a voltage-controlled bus. Table II provides parameters of the diesel generator set used based on a manufacturer's datasheet [8] and empirical data [9].

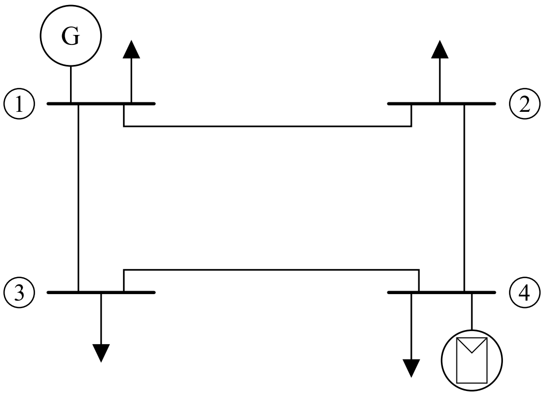

Fig. 4. Four bus system used for validation

Table II. – Genset parameters used

Parameter	**Unit**	**Value**
Generator		Marathon 1020FDH7095
Voltage	kV	11
Apparent Power	kVA	1590
Nominal current	A	83
Engine max. power	kW_m	1420
nominal $\cos\phi$		0.8
Approx. inertia [9]	s	6

The generator's nominal apparent power $S = 1590\,\text{kVA}$ and nominal voltage $V = 11\,\text{kV}$ were taken as base values. All other data is given in per units relative to this base. The generator's overload capacity is 12%. The nominal droop of the generator is 5% as shown in Figure 2.

The data on consumption and generation in each bus are given in Table III while Finally, Table IV provides the data on admittance of each line (at nominal frequency).

Table III. – Bus data

Bus No.	**Gen. [p.u.]**		**Load [p.u.]**		**Voltage$^+$ [p.u. ∠ °]**		**Bus type**
	P	Q	P	Q	$\lvert V\rvert$	∠	
1			0.15	0.093	1	0	Slack
2	0	0	0.275	0.170	1	0	PQ (load)
3	0	0	0.15	0.093	1	0	PQ (load)
4	0.25	0	0.1	0.062	1.02		PV (gen)

$^+$ Initial voltage used for method initalization

Table IV. – Line admittance at nominal frequency

Bus No.	**Series Y**		**Shunt Y**	
	G [p.u.]	B [p.u.]	TC [p.u.]	$Y/2$ [p.u.]
1–2	3.816	-19.078	0.103	0.052
1–3	5.170	-25.848	0.076	0.0388
2–4	5.170	-25.848	0.076	0.0388
3–4	3.023	-15.119	0.128	0.064

TC: Total line charging (static compensation).

The simulation was conducted for two conditions: without variation of frequency (the frequency value is kept at the nominal level) and with the effect of generator's droop.

A. Enhanced power flow

The Gauss-Seidel method implies an iterative approach to solution until the results of calculations stop varying considerably, i.e. the difference between the results obtained at each iteration does not exceed a certain value.

For demonstration purposes, however, this function was switched off and a fixed number of iterations was set.

B. Generator controls

Figure 5 shows the block diagram of the proposed generator controls based on information about the time response of the diesel system T_m and inertia of the genset H together with the droop K. This block diagram has been converted to a single transfer function and discretized using the same pole map method to produce a discrete function dependent on the sampling time T_s.

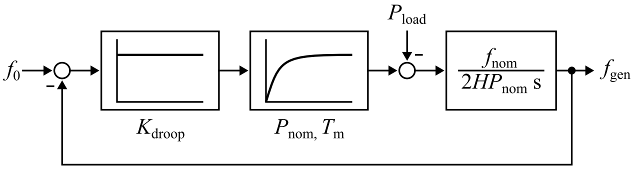

Fig. 5. Block diagram of the dynamics of generator controls

6. Results

A. Enhanced power flow

In both cases (with and without frequency variation) the algorithm provided rather quick convergence. In the figures below, the diagrams illustrate changes of the main parameters with each iteration when frequency variation is considered.

Figure 6 illustrates that the voltages quickly converge to their final values. It takes more iterations for the currents to converge, as shown in Figure 7. The line 1–2 is the most loaded, its current reaches ca. 1.9 p.u. value. That is why it is taken for comparative analysis.

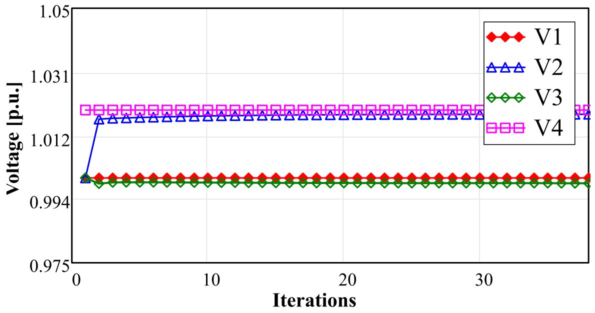

Fig. 6. Convergence of bus voltages

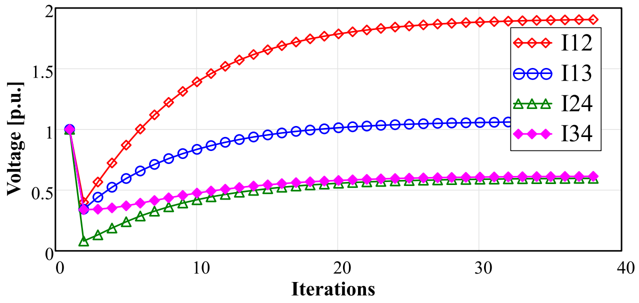

Fig. 7. Convergence of bus currents

Figure 8 shows that active and reactive components of the slack bus, i.e. the power demand from the diesel generator, steadily converge to their stable values with a convergence rate similar to the of bus currents, as expected.

Figure 9 illustrates that for the given loads the frequency is less than nominal, its value doesn't vary much during the iterations. Finally, Figure 10 represents the calculation of active and reactive components of power losses in the lines.

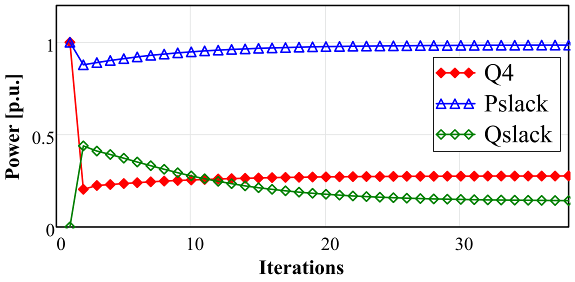

Fig. 8. Convergence of active and reactive powers

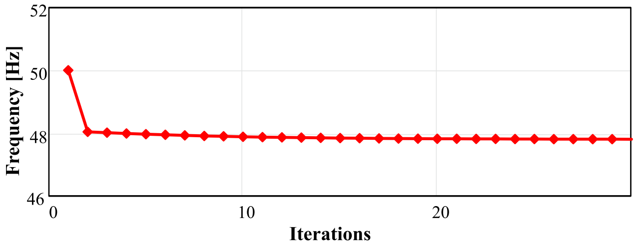

Fig. 9. Convergence of system frequency

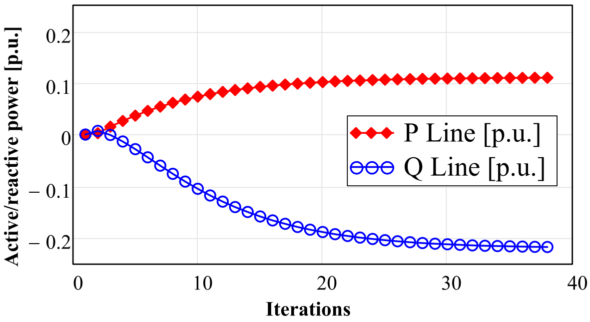

Fig. 10. Convergence of line losses

The results of the simulation, summarized in Table V show that account of frequency in power flow calculation has no effect on the voltages, currents, active and reactive power components. The biggest effect of considering frequency is in losses of reactive power in the lines. Within the range of nominal load, the difference of reactive power losses may reach up to 5%.

It should also be noted that the convergence of the algorithm is sometimes not possible, especially when the load exceeds the nominal value, which is however not plausible on a real system. Convergence problems of the algorithm are known [10] and shall be addressed in further research.

Table V. – Comparative summary on simulation

Parameter	$f = f_{\text{nom}}$	$f = f(P)$	**Difference**
Max. current $I_{1,2}$ [p.u.]	1.885	1.883	negligible
Reactive power at slack node Q_1 [p.u.]	0.151	0.149	1.3%
Active losses in all lines [p.u.]	0.112	0.110	1.8%
Reactive losses in all lines [p.u.]	0.223	0.212	5%

TC: Total line charging (static compensation).

B. *Time step dependency of generator controls*

The results of the algorithm, which simulates transient processes with different time steps, are shown in Figure 11. As expected, smaller time steps represent the dynamics of the system better. Nevertheless, for analyses requiring less detail but longer simulation horizons, big time steep can be used without harming static frequency response of the system at a certain constellation.

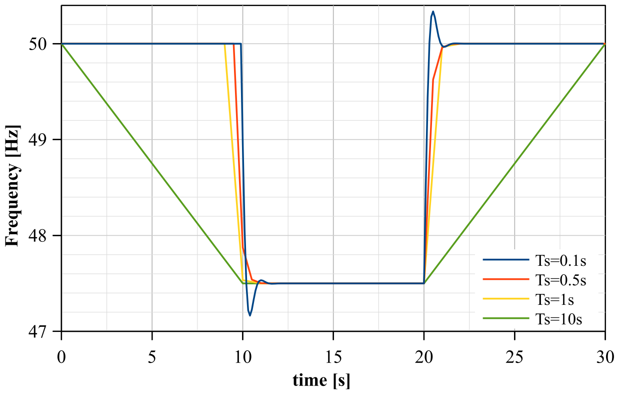

Fig. 11. The effect of similar time steps on system dynamics

7. Conclusions and further work

This paper described a novel method for performing power flow calculations, which can be used to verify viability and evaluate the feasibility of grid configurations by integrating the frequency component.

It has proven that for island grids it is critical to employ real dynamic performances of diesel generators, which implies using more complex dynamic models for system analysis. Simplified approaches that assume constant frequency of generators may lead to omitting situations when permissible levels are violated.

In particular, it is shown that for island grids with generators operated in droop speed control mode, frequency variation must be taken into account. Neglecting frequency in calculations leads to the error of estimation of line reactive power losses of ca. 5%.

A. *Further work*

It is shown that using big time steps for generator model doesn't reveal the sections of transients when frequency limit is actually violates the limit. Thus, there are still two contradicting goals to be achieved: running simulation for the periods long enough to assess economic feasibility (years) but at the same time with time steps small enough (seconds) not to miss violations.

Hence, on the modelling of generator controls there are the following open points to be addressed: the dynamic response on isochronous systems and the modelling of the dynamics of the voltage regulation (like typical AVRs[2]).

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[2] Automatic Voltage Regulators

Further research is needed to identify moments or conditions for which to run simulations with smaller time steps. These conditions can be initially estimated from load profiles but can be greatly enhanced by probabilistic functions of e.g. photovoltaic generation and/or load variations.

8. Acknowledgements

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