# Generic Equivalent Collector System Parameters for Large Wind Power Plant

J. Brochu, *Senior Member*, *IEEE*, R. Gagnon, and C. Larose

***Abstract*--This paper provides a set of generic equivalent collector system (ECS) parameters for preliminary power system studies of large wind power plants (WPP) represented by a single-wind turbine generator models. The accuracy that can be expected with a generic ECS is quantified for WPPs in the range of 100 to 300 MW. Express in pu of any WPP basis, the generic ECS parameters are constants. For a sample of ten WPPs used as reference cases, the generic ECS provides ECS models whose accuracy is adequate for prospective studies**

***Index Terms*— Aggregation , collector system, modeling, power systems, simulation, wind, wind power generation.**

## I. Introduction

GENERIC and simplified models of large wind power plants (WPP) are required for prospective studies of installation for which little is known in advance as well as for planning activities of existing facilities conducted by regional reliability organizations [3]. This industry need is currently addressed by different organizations worldwide. Notably, by the Wind Generation Modeling Group (WGMG) of the Western Electricity Coordinating Council (WECC) who has published a guide on WPP modeling [4].

Recently, an exhaustive validation of the equivalencing technique promoted by the WGMG has been conducted [5]. It has been shown that wind turbine generators (WTG) of the same type can be aggregated together and represented in fast transient, stability and load flow studies by an equivalent WPP made of only one equivalent WTG, one equivalent collector system (ECS) and the actual station step up and grounding transformers as shown in Fig. 1.

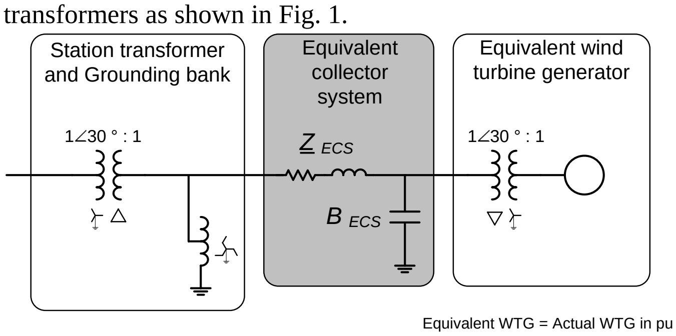


Fig. 1. Equivalent wind power plant as per the WGMG.

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Aggregation of WTGs is a straightforward process as long as the model of the WTGs to aggregate is defined in per unit. All is needed then is to change the WTG power basis accordingly to the nominal power of the complete WPP.

As for the collector system, the problem is more complex given the number of lines and cables, the variety of conductor sizes and the large diversity of series and parallel connections. To get an ECS that behaves just like a complete and detailed one, even for fast transient simulations, the National Renewable Energy Laboratory (NREL) method as shown to be accurate and easy to implement using a spreadsheet [1], [2] , and [5]. This method for aggregating the elements of a collector system requires the input of all lines and cables impedances and susceptances while taking into account the number of WTGs located upstream to each element.

Based on the work presented in this paper, getting an ECS using another approach that shows as good accuracy as the NREL one is probably feasible but this could not be a simple scale up procedure similar to that used for the WTGs. Whatever the method envisioned, it should take into account some specificities of each collector system to model.

Hence, a good solution for aggregating the collector system of existing WPPs is readily available for performing planning activities by regional reliability organizations. However, for prospective studies, little is known about possible WPPs and the NREL method, or another one based on actual collector system description, could not be used. Typically, only the main WPP characteristics such as nominal power, and voltage at the interconnection point are known. Sizing the station and grounding transformers is quite strait forward. The type of the WTG, typically 3 or 4 nowadays, might not be known but sizing can also be a simple matter provided that WTG model is in pu. Not much data is however available about the collector system. Although, a number of rules of thumb can be thinking of to estimate the ECS parameters, the impact of these educated guesses on the simulations are not well known.

This paper provides a set of generic ECS parameters that can be used for preliminary power system studies of large WPPs. The accuracy that can be expected with a generic ECS is quantified for WPPs in the range of 100 to 300 MW. Just like in the case of WTGs, these parameters express in pu of the WPP are constants. As shown in what follows for a sample of ten WPPs used as reference cases, a simple scale up of the generic ECS provides ECS models whose accuracy is adequate for prospective studies.

## II. NREL Equivalent Collector System

The NREL method for aggregating a WPP collector system, [1], [2] and [4], leads to the following two equations for the series impedance $\underline{Z}_{ECS}$ and the shunt susceptance $B_{ECS}$ of the ECS shown in Fig. 1:

$$\underline{Z}_{ECS} = \frac{\sum_{i=1}^{n_{line\ \&\ cable}} \underline{Z}_i \; n_{upstream\ \ WTG\ i}^2}{n_{total\ WTG}^2} \tag{1}$$

$$B_{ECS} = \sum_{i=1}^{n_{line\ \&\ cable}} B_i \tag{2}$$

where, $\underline{Z}_i$ and $B_i$ are the series impedance and the shunt susceptance of a line or a cable of the actual collector system, $n_{upstream}$ is the number of WTG located upstream to the line or cable and $n_{total\ \ WTG}$ is the total number of WTGs connected to the collector system.

These equations rely on three simplifications that are verified in practice:

- Currents in the collector system susceptances are negligible.
- Voltages across the collector system impedances are negligible.
- All WTGs inject in the collector system currents which have same amplitude and phase.

TABLE I contains ECS parameters calculated using the NREL method applied to ten actual WPPs. WPP 1 to 7 data come from [4] while WPP A to C data come from Hydro-Québec. With only one percent of overhead conductors, WPP A is placed in the group of WPP whose collector systems are underground.

For each WPP, pu are expressed on the nominal collector system voltage and the nominal WPP apparent power basis. Here, all nominal collector voltages are 34.5 kV. As for the WPP apparent power, a typical power factor of 0.9 is used.

TABLE I
Equivalent Collector System Parameters of 10 Actual WPPs

| | WPP | $P_{nom}$ | Overhead | $R_{ECS}$ | $X_{ECS}$ | $B_{ECS}$ |
|---|---|---|---|---|---|---|
| | | (MW) | (%) | pu | pu | pu |
| Underground | 1 | 100 | 0 | 0.0189 | 0.0156 | 0.0270 |
| | A | 100.5 | 1 | 0.0239 | 0.0113 | 0.0291 |
| | B | 109.5 | 0 | 0.0220 | 0.0103 | 0.0463 |
| | 2 | 110 | 0 | 0.0147 | 0.0134 | 0.0295 |
| Undergr. and Overhead | 3 | 100 | 33 | 0.0200 | 0.0878 | 0.0270 |
| | C | 109.5 | 22 | 0.0250 | 0.0305 | 0.0303 |
| | 4 | 200 | Some | 0.0156 | 0.0556 | 0.0248 |
| | 5 | 200 | 25 | 0.0222 | 0.0867 | 0.0446 |
| | 6 | 300 | Some | 0.0167 | 0.0667 | 0.0255 |
| | 7 | 300 | Some | 0.0200 | 0.0867 | 0.0450 |

## III. Generic Equivalent Collector System Parameters

### *A. Overview of Equivalent Collector System Parameters*

To better put into perspective some data contains in TABLE I, ECS parameters with known overhead percentages are plotted as a function of these percentages in Fig. 2.

It can be seen that collector resistances fall within a relatively narrow range located between 0.0147 and 0.025 pu. Furthermore, no significant relation can be established between the collector resistance and the percentage of overhead conductor. The same is true for the collector susceptances whose values lye between 0.0255 and 0.0463 pu.

However, collector reactances cover a much broader range of values which clearly fall within two ranges related to the presence or not of a significant percentage of overhead conductors. Near zero overhead conductor percentage, collector reactances are within 0.0103 and 0.0156 pu. They remain within 0.0305 and 0.0878 pu otherwise.

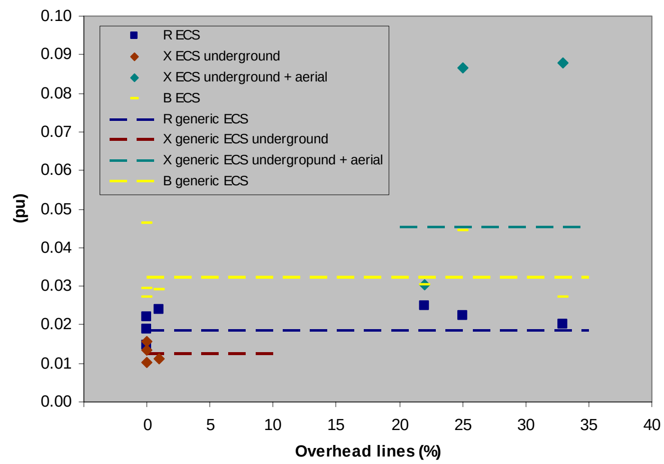


Fig. 2. ECS parameters for seven WPPs of TABLE I plotted as a function of the percentage of overhead lines. Dashed lines show the generic ECS parameters introduced in section III-*D*.

### *B. Equivalent Collector System Reactances*

Since TABLE I data are in pu of each individual WPPs, all these equivalent collector parameters are defined for WPPs delivering 1 pu power output. Under these conditions, the existence of the two different ranges of collector reactances cannot be related to the level of power flow. *These two ranges can neither be related only to the percentage of overhead conductors. Comparing the WPPs C to 5, we see an increase in the collector reactance by a factor 2.8 while the percentage of overhead conductors increases by a factor of 1.1 only*.

Although it is a fact that collector system losses are mainly attributed to the conductors nearby the WPP substation, where all the WTGs currents converged, it seems hazardous to only relate the large differences in the equivalent collector reactances to the fact that overhead conductors might be or not subjected to a large percentage of all the WTG currents as done in [4]. It is mentioned that the 33% of overhead conductors of WPP 3 carries 100% of WTG currents while the 25% of overhead conductors of WPP 5 carries 50% of WTG currents. If such relation were the only factor to take into account, with more overhead and twice as much current in these conductors, the WPP 3 collector reactance should be much higher than that of WPP 5, which is not the case. They are in fact almost equal. Besides, the resistance for the collector system with 33% overhead is even lower than for the other case with 25% overhead.

*At the time of writing, authors are not in a position to provide any satisfactory explanation for the differences in collector reactances although we suspect that a possible explanation could be related to the type of overhead conductors used. Identification of one or more main explanations for the differences in collector reactance remains to be made.*

### C. Sensivity of ECS Parameters to Line and Cables Characteristics

It has been shown [5] that, although not negligible, ECS parameters only has a slight impact on the active and reactive power at the output of an equivalent WPP. This is illustrated in Fig. 3 where the green active and reactive powers for WPP B are obtained using the proper ECS parameters. The two other traces are obtained when only the ECS parameters are changed, that is increased of lowered by 10%.

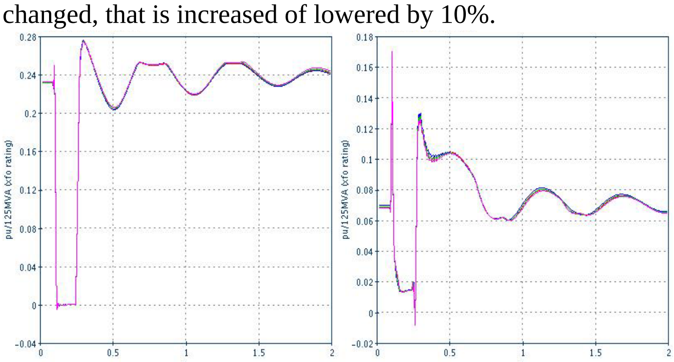

Fig. 3. Active and reactive powers obtained at the output of an equivalent WPP. Very slight differences are observed for arbitrary 10% increase (blue) and a 10% reduction (magenta) of the ECS parameters as compared to the reference case (green).

The three traces being hardly distinguished one from the other it is clear that simulations are not very sensitive to the ECS parameters.

### D. Calculation of Generic Equivalent Collector System Parameters

The relatively limited ranges of ECS parameters for very different WPPs and the low sensitivity of the electrical output of an equivalent WPP to its ECS parameters are the two key observations that lead to the generic ECS parameters proposed in this paper. Since these parameters lies within four narrow ranges, one for the resistances, one for the susceptances and two for the reactances, we calculated four generic parameters, one constant for each range.

The criteria used for calculating each generic ECS parameter is that the two extreme differences in percent, between the generic ECS parameter and the highest and the lowest values encountered within the range of the ECS parameters, be equal in absolute value. That is, taken the ECS resistance as an example and eliminating the factor 100 on either side of the equal sign:

$$\frac{R_{gen\ ECS} - R_{ECS\ \min}}{R_{ECS\ \min}} = \left| \frac{R_{gen\ ECS} - R_{ECS\ \max}}{R_{ECS\ \max}} \right| \tag{3}$$

The generic ECS resistance is then given by:

$$R_{gen\ ECS} = \frac{2\, R_{ECS\ \min}\, R_{ECS\ \max}}{R_{ECS\ \min} + R_{ECS\ \max}} \tag{4}$$

The three other generic parameters corresponding to the three other ranges of ECS parameters are calculated using three equations of the same form than (4) where letter $R$ is simply replaced by $B$ or $X$ . The highest and lowest values for the ECS parameters come from TABLE I.

The generic ECS parameters obtained are indicated in TABLE II and shown in Fig. 2 by dashed lines. The ranges of variations Δ for the resistances and the susceptances are ±26% and ±30% respectively. For the two reactances, one for a collector system made of underground cables only and the other for a collector system made of a mix of underground cables and overhead lines, the ranges of variations are ±20% and ±48% respectively.

TABLE II
COMPARISON OF THE GENERIC ECS PARAMETERS WITH THE ECS PARAMETERS OF TABLE I

| | WPP | $R_{gen\ ECS}$ | $X_{gen\ ECS}$ | $B_{gen\ ECS}$ | $\Delta R$ | $\Delta X$ | $\Delta B$ |
|---|---|---|---|---|---|---|---|
| | | pu | pu | pu | % | % | % |
| Underground | 1 | 0.0185 | 0.0124 | 0.0322 | -2 | -20 | 19 |
| | A | | | | -23 | 10 | 11 |
| | B | | | | -16 | 20 | -30 |
| | 2 | | | | 26 | -8 | 9 |
| Undergr. and Overhead | 3 | 0.0185 | 0.0453 | 0.0322 | -8 | -48 | 19 |
| | C | | | | -26 | 48 | 6 |
| | 4 | | | | 19 | -19 | 30 |
| | 5 | | | | -17 | -48 | -28 |
| | 6 | | | | 11 | -32 | 26 |
| | 7 | | | | -8 | -48 | -28 |

## IV. ACCURACY OF A GENERIC EQUIVALENT COLLECTOR SYSTEM

### A. Methodology

To verify the adequacy of generic a ECS for preliminary power system studies of large WPP, a sensivity study was performed using the ECS of WPP B whose equivalent model conformity have previously been fully validated against a complete and detailed model [5]. The main outcomes of this study are illustrated in this section with five sets of nine simulations each.

As indicated in TABLE IV, these five sets of simulations are characterized by the type of fault applied on the power system side of the equivalent WPP B and the active and reactive power outputs of its equivalent WTG.

TABLE III

OPERATING CONDITIONS USED FOR ILLUSTRATING THE ADEQUACY OF THE GENERIC EQUIVALENT COLLECTOR SYSTEM PARAMETERS

| Operating conditions | | |
|---|---|---|
| Fault type | WTG output (pu) | |
| | P | Q |
| ABCG | 0.9 | 0.18 |
| AB | 0.9 | 0.18 |
| AG | 0.9 | 0.18 |
| ABCG | 0.9 | –0.24 |
| ABCG | 0.5 | 0.19 |

Each set of simulations includes one simulation done using the ECS parameters plus one simulation for each different combination of variations in ECS parameters listed in TABLE IV. In all cases, active and reactive powers as well as voltage and current were monitored at the output of the ECS of WPP B. Finally, the four electrical outputs of the ECS using the eight combinations of parameter variations were compared to those obtained with the unmodified ECS parameters.

TABLE IV

VARIATIONS TESTED IN EQUIVALENT COLLECTOR SYSTEM PARAMETERS

| $\Delta R$ | $\Delta X$ | $\Delta B$ |
|---|---|---|
| % | % | % |
| –30 | –50 | –30 |
| –30 | –50 | +30 |
| –30 | +50 | –30 |
| –30 | +50 | +30 |
| +30 | –50 | –30 |
| +30 | –50 | +30 |
| +30 | +50 | –30 |
| +30 | +50 | +30 |

Since:

- ECS in TABLE I are based on actual WPPs;
- NREL equivalencing technique has been validated;
- Worst deviations in TABLE II between generic ECS parameters and ECS are known for a significant number of actual WPPs
- TABLE IV variations in ECS parameters are larger or equal to those listed in TABLE II;

one can expect that TABLE IV combinations of ECS parameter variations, applied to the NREL ECS parameters of a given equivalent WPP, should lead to extreme differences in electrical quantities at the ECS output that will most probably be larger than differences obtained at the output of an ECS based on generic ECS parameters. Hence, provided that extreme differences are acceptable for prospective studies of large WPPs, the generic ECS adequacy will be demonstrated.

Given the relatively limited number of seven WPPs used for calculating the generic parameters, it is understood that more WPPs should ideally be used for validating thoroughly the adequacy of the generic ECS parameters.

For all simulations presented in the next two sections, the equivalent WPP is connected to a network whose short-circuit level is 3.3 times the WPP nominal power. This relatively low ratio tends to increase the impact of collector system variations as compared to another situation with a higher ratio. As a matter of fact, the lower the ratio, the more sensitive voltages and currents are at the output of the collector system.

Faults are applied at 0.1 s and last nine cycles. Fast transient simulations were done using Hypersim where a detailed model of a type-3 WTG was implemented.

*B. Nominal Active Power Generation Together with Reactive Power Generation*

Fig. 4Nine traces are shown, one using the ECS parameters and eight for each combination of parameter variations listed in TABLE IV. The positive sequences of the phase-to-ground voltage and line current at the output of the ECS are shown in Fig.
5.

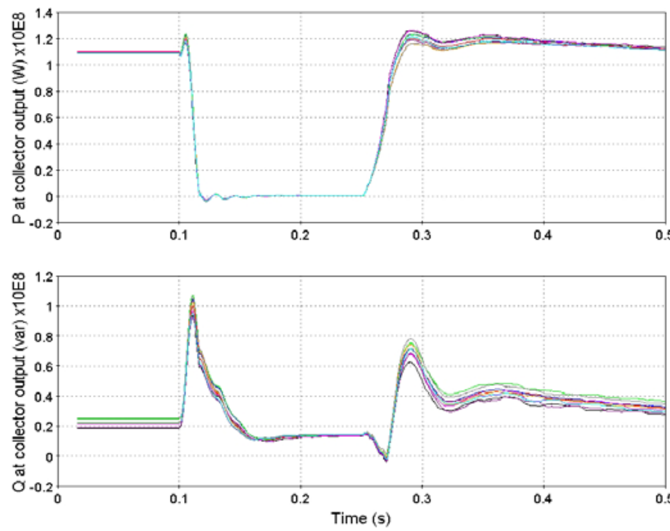


Fig. 4. Active and reactive powers at the output of the ECS as a result of 9-cycle three-phase faults applied at 0.1 s at the equivalent WPP B terminals.

It can be seen that electrical quantities corresponding to the ECS parameters and their variations can hardly be distinguished one from the others. As a matter of fact, those corresponding to the ECS parameters are located in the center of the traces while the eight others are located on both sides of it.

Since it is difficult to have an objective evaluation of the differences related to the electrical quantities resulting from the variation in ECS parameters, we first calculated for each electrical quantity the maximum and minimum envelopes that contain all other traces. Then, we expressed in percent, on the system basis of the WPP, the differences between these envelopes and the trace corresponding to the unmodified ECS parameters.

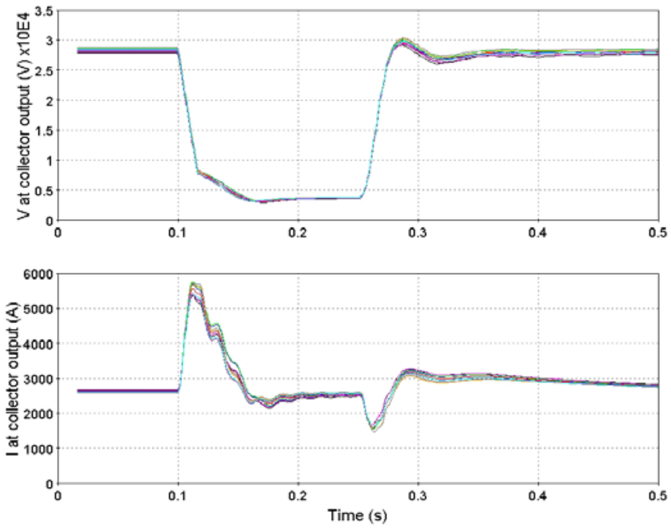


Fig. 5. Positive sequences of voltage and current corresponding to Fig. 4 at the output of the ECS.

The extreme differences obtained for the three-phase fault of Fig. 4 are shown in red in Fig. 6 and Fig. 7. On these figures, extreme differences are also shown in blue for a phase-to-phase fault and in green for a phase-to-ground fault. The first three operating conditions of TABLE II can then be directly compared.

It can be seen that differences in steady state are lower than 3% for the active and reactive powers. From the application of the faults and later on, all differences remains within 8%.

In steady-state, envelopes of differences in positive sequence voltages and currents at the output of the ECS are within 3% here also. Under fault conditions, voltage differences are quite similar in amplitude for all fault types, they remain within 3%, current differences however are much larger for the three-phase fault, for which they transiently reach 15%, than for the unbalanced faults.

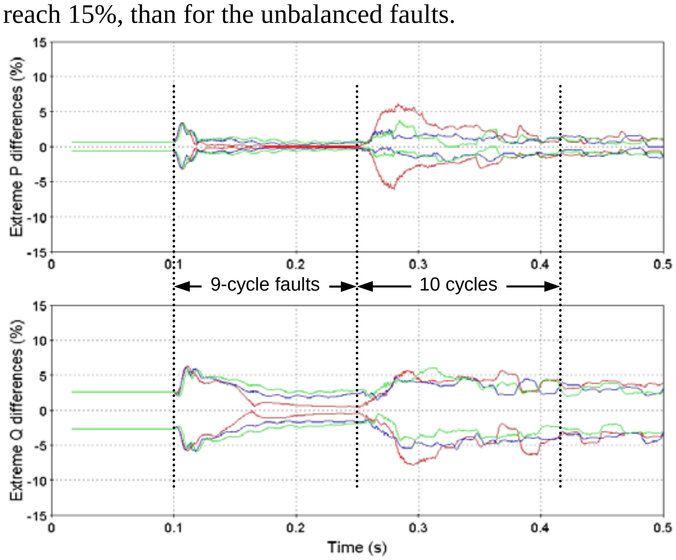


Fig. 6. Envelopes of extreme differences in P and Q at the output of the ECS as a result of 9-cycle three-phase (in red), phase-to-phase (in blue), and phase-to-ground (in green) faults applied at 0.1 s at the WPP terminals.

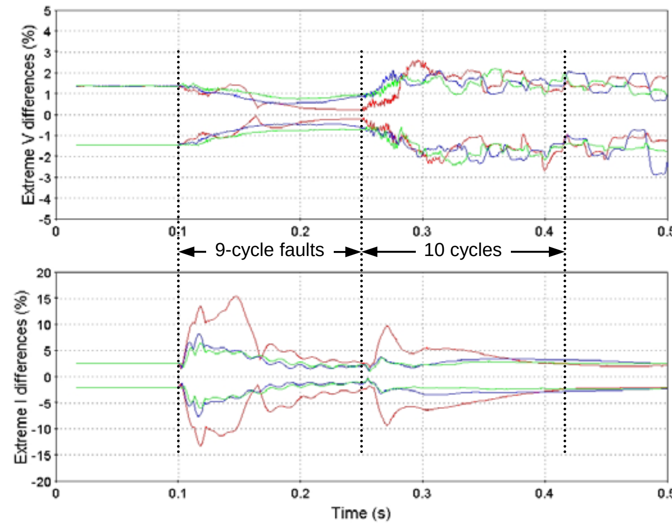


Fig. 7. Envelopes of extreme differences in V and I at the output of the ECS as a result of 9-cycle three-phase (in red), phase-to-phase (in blue), and phase-to-ground (in green) faults applied at 0.1 s at the WPP terminals.

## *C. Other Operating Conditions*

The active and reactive power extreme differences for the first and the last two operating conditions in TABLE III are compared in Fig. 8. For the traces in red, prefault active and reactive powers are respectively set to 0.9 and 0.18 pu and the fault is balanced. These traces are the same red traces plotted in Fig. 6. In blue, prefault active and reactive powers are 0.9 and –0.24 pu while in green they are set to 0.5 and 0.19 pu.

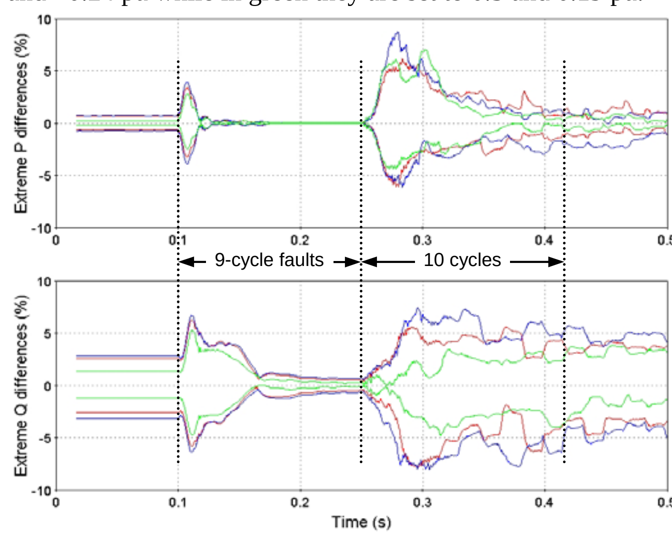


Fig. 8. Envelopes of extreme differences in P and Q at the output of the ECS as a result of 9-cycle three-phase faults applied at 0.1 s at the WPP terminals. Same sets of ECS parameters are used as in Fig. 1. In red P=0.9 and Q=0.18 pu, in blue, P=0.9 and Q= –0.24 pu, and in green P=0.5 and Q=0.19 pu.

We see here that all extreme differences lye within 3% in steady-state and reaches 9% following a three-phase fault. Globally, we can conclude that variations in active or reactive powers during prefault operating conditions do not have a significant impact on the extreme differences before and after application of a three-phase fault. As per Fig. 6, application of unbalanced faults will result in less severe differences than for a balanced fault.

## V. Discussion

Section III-*A* observations and section IV-*B* simulations have shown that a very limited set of generic ECS parameters are adequate for modeling large WPPs for prospective load-flow, stability and fast transient studies since all steady-state extreme differences are lower than 3% while post fault differences remain below 10% and decrease below 5% within ten cycles.

Regarding the ECS reactance, *the presence or not of significant percentage of overhead conductors appears to be the only topological characteristic of a prospective WPP worth to be estimated. A larger number of WPP would certainly help improving and validating the method presented here. In particular, this would allow covering the gap visible in Fig. 1 for percentage of overhead conductor between 0 and 20 %. Together with the WPPs' ECS parameters, a good approximation of the percentage of overhead conductors and some information regarding their lineic impedances could also help better understand the most appropriate way of selecting the generic ECS reactance in particular.*

*One outcome of such survey might lead to a better or wider set of generic ECS parameters related to one or two specific characteristics of WPPs. For instance, WPP C with 22% overhead and a relatively low collector reactance could be, accordingly to a criteria that remains to be defined, included in a different group than WPP 5 that has a similar percentage of overhead conductors but exhibit a much larger collector reactance. As a result, more than four generic ECS parameters could be identified which would improve simulation conformity with simulations performed with the ECS parameters. For now, with only three WPPs whose percentages of overhead conductor are known, definition of more than one collector reactance for overhead conductors would be hazardous considering the already small sample of three data.*

## VI. Conclusion

A set of generic ECS parameters that can be used for preliminary power system studies of large WPPs has been derived and the adequacy of these parameters has been validated for a sample of ten WPPs in the range of 100 to 300 MW.

Active and reactive powers, voltages and currents at the output of the ECS of an equivalent WPP have been used for ascertaining the adequacy. Using an ECS based on the NREL aggregation technique as reference case, and applying a complete set of large variations to these parameters allowed quantifying the extreme differences taken by the electrical quantities at the collector output as a result of these variations. Since the generic ESC parameter values lye typically within the range of variations applied to the NREL ESC parameters, differences between the electrical quantities measured at the output of the generic ECS and the NREL ECS should be lower than the extreme differences. That is, pre fault differences should be lower than 3% while post fault differences should remain below 10% and decrease below 5% within ten cycles.

The ESC parameters express in pu of the WPP are constants which renders their utilization straightforward.

## VII. References


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## VIII. Biographies

**Jacques Brochu** (M'86-SM'06) obtained his B.A.Sc. and M.A.Sc. degrees in electrical engineering from Université Laval in Québec City in 1981 and 1986 respectively and his Ph.D. degree from École Polytechnique de Montréal in 1997.
From 1981 to 1983, he was production engineer for Canadian General Electric. He is currently a research engineer at IREQ (Hydro-Québec's research institute) where he has worked since 1985. From 1990 to 2002 he was seconded to the Centre d'Innovation sur le Transport d'Énergie du Québec (CITEQ) in Varennes, Qc. His main areas of interest include power electronics and power flow control devices for power systems. He has been involved in the development of the Interphase Power Controller (IPC) technology and is the author of a reference book on the subject.

**Richard Gagnon** was born in Québec, Canada in 1966. He obtained his B.Sc.degree in physics engineering in 1990, his M.Sc. degree in electrical engineering in 1992 and his Ph.D. degree in electrical engineering in 1997, all from Université Laval (Québec). From 1996 to 2001, he was professor of electrical engineering at Université du Québec à Rimouski. Since 2001, he is a research engineer at IREQ (Hydro-Québec's research institute). His area of professional interests includes modeling and simulation of power system devices and wind turbines.

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He joined Institut de recherche d'Hydro-Québec (IREQ) in 1996 as a development engineer in the Power System Simulation Laboratory. His main interest is in the numerical real-time simulation of power systems.