Robustness testing of two impedance estimation techniques in weak grids

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Abstract

Due to instability issues that arise in weak grids, knowledge of the grid impedance can improve the performance of converters connected to such networks. The existing method of active and reactive power variation is adapted to weak grid control, where the active power and voltage magnitude are varied instead. The impedance estimation is undertaken either algebraically using two sets of measurements at two different operating points, or using the recursive least squares technique with multiple measurements at multiple different operating points. It is demonstrated that the recursive least squares estimation technique yields the most reliable results for inductance estimation for various short circuit levels, network types and noise levels. The optimal variation of active power and voltage magnitude are identified for robustness against system variability. It is also shown that at transmission level X/R ratios, the estimation for resistance is poor.

1 Introduction

To reach the intended carbon reduction targets, such as the European Commission's target of being carbon neutral by 2050 [1], it is essential to replace fossil fuel based power stations with renewable energies and to electrify heating and transport [2]. This target is hindered by several economic, institutional, technical and socio-economic barriers [3], with the grid integration of renewable energies being one of the main technical obstacles.

One aspect of grid integration is the integration of converter-based renewables in weak grids. Grid strength is defined by short circuit ratio (SCR), whereby a weak grid has an SCR of less than 3 [4]. $SCR = \frac{E^2}{S_{rated} Z_{grid}} = \frac{S_{sc}}{S_{rated}}$ where E is the grid voltage, S_{rated} is the converter rating, S_{sc} is the short circuit level power and Z_{grid} is the grid Thevenin equivalent impedance [5] [6]. The grid impedance, one of the defining factors of SCR, is largely influenced by transmission capacity and length; large distances between renewable energies and large generation plants or demand centres increases the equivalent grid impedance, resulting in a low SCR [7].

While a converter can be tuned to be stable at a specific grid impedance, grid impedance will change, potentially making the converter unstable [4]. The use and implementation of impedance estimators, together with adaptive control strategies, could be a solution [8]. There are three main types of estimation methodologies discussed in the literature, as follows:

- [9] excites the system by injecting a noncharacteristic harmonic current of 75 Hz, and analyses the system response with Fourier analysis. This form of estimation requires the system to settle to steady state, and only allows for the etimation of the impedance at the fundamental frequency.
- [8] utilises a single current spike injection to perturb the system, and again uses Fourier analysis to decompose the measurements. However, the Fourier analysis is undertaken on the transient response of the system, making it both quicker and more distruptive then the noncharacteristic harmonic current injection method.
- [10] varies active and reactive power (P and Q, respectively) in the control outer loop to introduce new operating points. The variation in operating points then allows for the impedance to be estimated either algebraically (using the measurements from two sets of operating points) or using recursive least squares (using measurements from more than two operating points).

Active and reactive power variation, as described in [10], is a sensible technique for the purposes of online controller tuning as it is undesirable to inject large or lengthy disturbances into a weak grid, whereas introducing gentle step changes in outer loop references are less disruptive [11]. It also determines the impedance at the fundamental frequency and therefore no assumption of impedance linearity is required.

The contributions of this paper are as follows:

- Assess the functionality of the P and Q variation technique in weak grids. In weak grids, the control outer loop is usually adapted to control active power and voltage magnitude (P and |U|) instead of P and Q [12]. As such, the research undertaken in this paper varies P and |U| in order to introduce new operating points.
- With the P and |U| varitation method, both the algebraic and the recursive least squares estimation techniques can be used. This paper aims to assess how well these estimation methods perform in weak grids and to determine the

optimum P and |U| variation magnitudes such that the estimation techniques are immune to a wide range of SCRs and measurement noise.

- Assess the performance of the estimation techniques at an X/R ratio representative of transmission networks. [10] uses an X/R ratio of 0.75, typical of low voltage distribution networks [13]. In this paper, an X/R ratio of 10 is used - in line with the transmission networks, such as [14] and [15].
- Assess the effect of complex networks on the quality of the Thevenin equivalent impedance estimation. Therefore, two different grids are implemented to further test the robustness of the impedance estimation techniques: an equivalent RL network as per Fig. 1b, as is standard in most impedance simulations, and a more complex network which contains a resonance, as per Fig 1c. These different network scenarios are designed to cover various network conditions which are unknown to the converter, as per Fig. 1a.

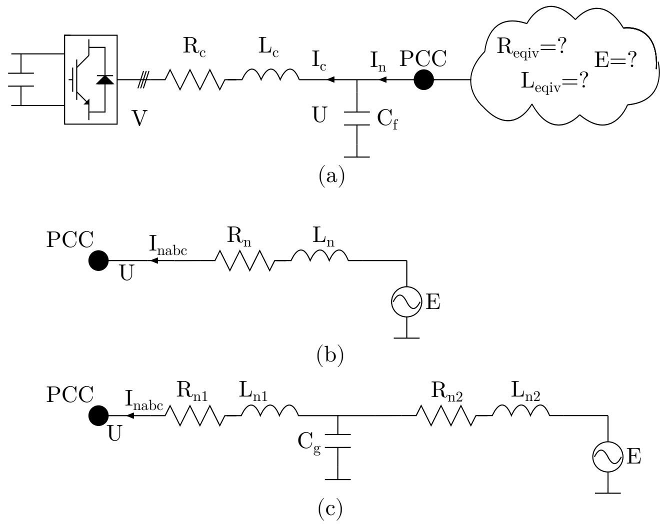

Fig. 1 (a) System under test with unknown grid parameters. (b) Thevenin equivalent (RL) impedance. (c) Complex impedance.

Section 2 gives some more details on how the estimation techniques are integrated into the controller and how the algebraic and the recursive least squares estimation techniques work; Section 3 describes how the testing is undertaken, and Section 4 displays the results of the tests. Section 5 discusses these results. Finally, section 6 concludes the paper.

2 Integration of estimators in the control

The P and |U| variations are introduced by the control outer loop, as per Fig. 2. This is a modification to the standard vector current controller in [16].

The assumptions required to build the mathematical expressions for the impedance estimation are explained below.

- Assume that the grid voltage (E) remains constant during the measurement period of a few seconds (stationary grid conditions).

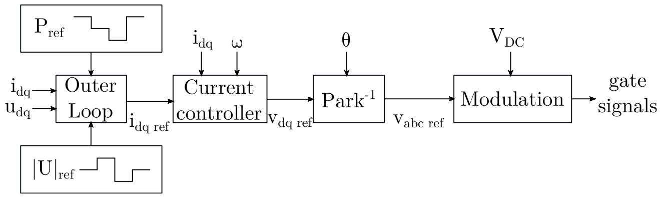

Fig. 2. Control structure with integrated P and |U| variations.

- System linearity is assumed. Thevenin equivalent impedance is therefore an appropriate representation of the network impedance.
- Phases are balanced and symmetric.

2.1 *Algebraic Estimation Technique*

The grid impedance can be determined by dividing the change in voltage (U) by the change in grid current (I_n) [10]. Note that the following dq-frame alignment is used: $A = a_q - ja_d$. The subscripts 1 and 2 represent two sets of measurements made at different operating points, where each operating point is achieved by reducing the reference of the power and the voltage magnitude in turn.

$$Z_{grid} = \frac{U_1 - U_2}{I_{n\,1} - I_{n\,2}} = \frac{-u_{q2} + u_{q1}}{-i_{nq2} + i_{nq1} + j(i_{nd2} - i_{nd1})} \quad (1)$$

By separating real and imaginary, the following equations can be determined for the grid resistance (R_{grid}) and the grid reactance (X_{grid}).

$$R_{grid} = \frac{(i_{nq1} - i_{nq2})(u_{q1} - u_{q2})}{(i_{nq1} - i_{nq2})^2 + (i_{nd1} - i_{nd2})^2} \quad (2)$$

$$X_{grid} = -\frac{(i_{nd2} - i_{nd1})(u_{q1} - u_{q2})}{(i_{nq1} - i_{nq2})^2 + (i_{nd1} - i_{nd2})^2} \quad (3)$$

Due to the lack of guidance on deviation size, a series of tests is undertaken to determine the optimal deviation. Power deviations of 2%, 1% and 0.5% are tested. Voltage deviations of 5%, 2.5% and 1.25% are tested. For illustrative purposes, a power deviation of 2% and a voltage magnitude deviation of 5% is demonstrated in Fig 3. The measurement points (as per (2) and (3)) are taken at the end of each step. Note that the length of the deviations is determined by the settling time, which is a direct function of grid conditions and controller tuning. As such, the time steps in Fig 3 are purely representative.

2.2 *Recursive Least Squares*

Unlike the algebraic estimation technique, the recursive least squares estimation technique can allow for many measurement points to be taken into account. The equation below is generalised to k measurement points, all undertaken at different operating points.

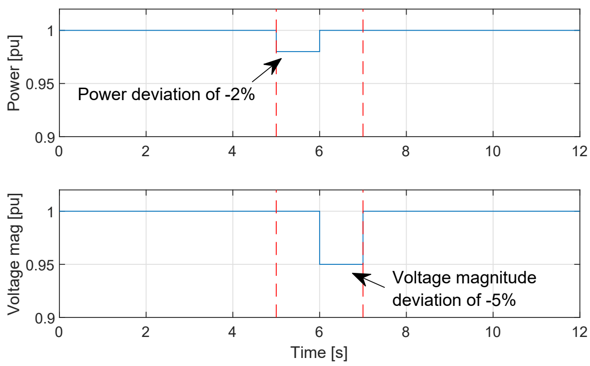

Fig. 3 Power and voltage magnitude output for the algebraic estimation techniques.

$$\begin{bmatrix} U_1 \\ U_2 \\ \vdots \\ U_k \end{bmatrix} = \begin{bmatrix} I_{n1} & 1 \\ I_{n2} & 1 \\ \vdots & \vdots \\ I_{nk} & 1 \end{bmatrix} \cdot \begin{bmatrix} Z_{grid} \\ E \end{bmatrix} \quad (4)$$

This can be written in vector notation:

$$\boldsymbol{Y} = \boldsymbol{A} \cdot \boldsymbol{X} \quad (5)$$

Whilst (5) is a good representation for the real grid, it does not reflect the fact that vector $\boldsymbol{X}$ is unknown, and should be treated as an estimated value. As such:

$$\begin{bmatrix} U_1 \\ U_2 \\ \vdots \\ U_k \end{bmatrix} = \begin{bmatrix} I_{n1} & 1 \\ I_{n2} & 1 \\ \vdots & \vdots \\ I_{nk} & 1 \end{bmatrix} \cdot \begin{bmatrix} \hat{Z_{grid}} \\ \hat{E} \end{bmatrix} - \begin{bmatrix} q_1 \\ q_2 \\ \vdots \\ q_k \end{bmatrix} \quad (6)$$

Where q represents the error of the estimation. Alternatively written as:

$$\boldsymbol{Y} = \boldsymbol{A} \cdot \hat{\boldsymbol{X}} - \boldsymbol{Q} \quad (7)$$

Where $\hat{\boldsymbol{X}}$ is the estimate of $\boldsymbol{X}$ and $\boldsymbol{Q}$ is the error between $\boldsymbol{X}$ and $\hat{\boldsymbol{X}}$.

To obtain the estimations with minimum error, the error cost function must be squared and derived, as explained in [17].

$$\boldsymbol{J} = |\boldsymbol{Q}|^2 = \boldsymbol{Q}^T\boldsymbol{Q} \quad (8)$$

$$\frac{\delta \boldsymbol{J}}{\delta \hat{\boldsymbol{X}}} = \frac{\delta \boldsymbol{Q}^T}{\delta \hat{\boldsymbol{X}}}\boldsymbol{Q} + \boldsymbol{Q}^T\frac{\delta \boldsymbol{Q}}{\delta \hat{\boldsymbol{X}}} = 0 \quad (9)$$

Which can be shown to be:

$$\hat{\boldsymbol{X}} = (\boldsymbol{A}^T\boldsymbol{A})^{-1}(\boldsymbol{A}^T\boldsymbol{Y}) \quad (10)$$

If implemented correctly, this method can give updates of grid voltage in the d and q components, and of equivalent impedance.

It is decided to test the recursive least squares estimation technique utilising five steady state measurements. For illustrative purposes, this is demonstrated in Fig 4. In this figure, the power deviations are $-[0\ 0.4\ 0.8\ 0.6\ 0.2]\%$ and the voltage magnitude deviations are $-3.3 \cdot [0.25\ 0.75\ 1\ 0.5\ 0]\%$. The measurements are taken at the end of each step.

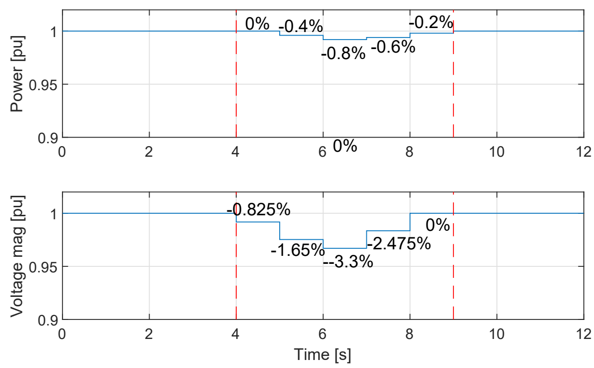

Fig. 4 Power and voltage magnitude output for the recursive least squares estimation technique.

3 Methodology

A series of tests is undertaken to assess the robustness of the algebraic and recursive least squares estimation techniques, as per Table 1.

Table 1 Robustness Testing

Test	Est. Technique	Grid Type	Equiv. SCR	Noise
A	Algebraic	RL	7 - 5 - 3 - 1.5	No
B	Algebraic	Complex	5.8 - 4 - 2.3	No
C	Algebraic	RL	7 - 5 - 3 - 1.5	Yes
D	Rec. Least Sq.	RL	7 - 5 - 3 - 1.5	No
E	Rec. Least Sq.	Complex	5.8 - 4 - 2.3	No
F	Rec. Least Sq.	RL	7 - 5 - 3 - 1.5	Yes

These tests are undertaken at different levels of power and voltage magnitude deviation. Tests C and F are subjected to noise added to the power network to simulate transients in the voltage and measurement noise.

4 Results

The simulation results are presented in Tables 2 to 7. Results within 5% are shaded green (dotted pattern); within 20%, the results are shaded amber (crosshatched pattern); and results more than 20% inaccurate are shaded red (diagonal pattern).The resistance estimations are generally poorer – this is due to the unfavourable X/R ratio of 10, making the resistance proportionally much smaller than the reactance. These results are included in this article to highlight the limitations of these methods when employed in high X/R ratio networks.

Table 2 Results for Test A: Algebraic estimation technique, RL grid, no noise simulated

		SCR 7		SCR 5		SCR 3		SCR 1.5	
P dev (%)	U dev (%)	L_{err} (%)	R_{err} (%)	L_{err} (%)	R_{err} (%)	L_{err} (%)	R_{err} (%)	L_{err} (%)	R_{err} (%)
2	5.0	0.3	31.1	0.5	3.7	1.2	-61.9	4.4	-230.2
2	2.5	0.7	16.1	1.0	-21.0	2.7	-102.6	9.4	-299.2
2	1.25	1.7	-22.9	2.7	-72.3	6.7	-173.7	21.7	-403.9
1	5.0	0.1	39.0	0.3	15.8	0.6	-43.5	2.6	-194.2
1	2.5	0.4	27.4	0.6	1.3	1.5	-63.5	5.0	-234.3
1	1.25	0.5	16.4	1.1	-21.2	2.3	-87.3	9.2	-293.5
0.5	5.0	0.1	44.8	0.1	19.3	0.3	-30.2	1.7	-174.8
0.5	2.5	0.1	43.2	0.2	16.1	0.5	-34.7	2.1	-183.1
0.5	1.25	5.8	28.7	0.7	5.8	12.2	-39.1	4.3	-224.5

Table 3 Results for Test B: Algebraic estimation technique, complex grid, no noise simulated

		SCR 5.8		SCR 4.4		SCR 2.3	
P dev (%)	U dev (%)	L_{err} (%)	R_{err} (%)	L_{err} (%)	R_{err} (%)	L_{err} (%)	R_{err} (%)
2	5	-0.4	14.7	-0.5	-14.1	1.4	-113.4
2	2.5	0.1	-6.8	0.3	-42.1	3.8	-162.2
2	1.25	1.5	-50.8	2.5	-98.7	9.9	-253.0
1	5	-0.6	24.4	-0.9	-0.8	0.6	-90.4
1	2.5	-0.3	13.1	-0.5	-15.2	1.7	-117.9
1	1.25	0.0	-0.4	0.2	-39.6	3.2	-148.1
0.5	5	-0.7	32.1	-1.0	5.7	0.0	-71.6
0.5	2.5	-0.6	28.7	-0.9	3.4	0.3	-80.0
0.5	1.25	0.3	6.9	-0.6	-10.9	7.4	-100.7

Table 4 Results for Test C: Algebraic estimation technique, RL grid, noise simulated

		SCR 7		SCR 5		SCR 3		SCR 1.5	
P dev (%)	U dev (%)	L_{err} (%)	R_{err} (%)	L_{err} (%)	R_{err} (%)	L_{err} (%)	R_{err} (%)	L_{err} (%)	R_{err} (%)
2	5.0	-0.3	62.5	-0.4	41.1	0.2	1.5	4.5	-242.7
2	2.5	2.6	205.0	1.0	50.2	2.4	103.0	8.5	-254.4
2	1.25	2.2	68.9	-10.6	18.1	5.0	-42.1	14.0	-426.4
1	5.0	-8.1	87.3	0.7	91.8	-7.5	16.4	2.1	-105.8
1	2.5	14.1	4.5	-2.4	69.3	14.0	-38.2	0.8	-183.0
1	1.25	8.8	-50.2	-4.5	87.3	9.6	-93.0	2.8	-192.6
0.5	5.0	-4.2	50.7	7.5	59.6	-3.9	-0.5	7.8	-157.2
0.5	2.5	-11.5	-79.8	12.0	138.1	-10.5	-116.3	8.6	56.8
0.5	1.25	34.6	198.5	28.3	76.2	34.3	180.8	26.2	-76.7

Table 5 Results for Test D: Recursive least squares estimation technique, RL grid, no noise simulated

		SCR 7		SCR 5		SCR 3		SCR 1.5	
P dev (%)	U dev (%)	L_{err} (%)	R_{err} (%)	L_{err} (%)	R_{err} (%)	L_{err} (%)	R_{err} (%)	L_{err} (%)	R_{err} (%)
P_{seq}	$U_{seq} \cdot 3.3$	0.0	66.1	0.0	51.2	-0.5	18.0	-1.3	-76.9
P_{seq}	$U_{seq} \cdot 4.15$	0.1	63.7	0.0	48.1	-0.4	11.5	-1.0	-84.2
P_{seq}	$U_{seq} \cdot 5$	0.1	61.9	0.0	45.8	-0.2	7.5	-0.8	-89.5

Power and Voltage Magnitude deviation sequences for the recursive least squares tests (Tests D, E and F) are as per (11) and are percentages.

$$\begin{aligned} P_{seq} &= -[0 \;\; 0.4 \;\; 0.8 \;\; 0.6 \;\; 0.2] \\ U_{seq} &= -[0.25 \;\; 0.75 \;\; 1 \;\; 0.5 \;\; 0] \end{aligned} \quad (11)$$

5 Discussion

Based on the results, the following observations are made regarding the algebraic and the recursive least squares estimation techniques individually.

- The algebraic estimation technique produces the best results when the |U| deviations are 5% – the largest available deviation. This suggests that voltage magnitude deviations are particularly effective at producing the required change in set-point. The various power deviations produce negligible differences in results.
- The recursive least squares estimation technique produces the best results for U_{seq} multipliers 3.3 and 4.15. However, the results are very consistent throughout.

When comparing the two estimation techniques against one another:

- In noise-free systems (as per Test A, B, D, E), the recursive least squares estimation technique produces marginally better results than the algebraic estimation technique. The estimation errors are more consistent for varying SCRs which gives increased confidence for good performance when the grid impedance is not known.
- With added white noise (as per Test C and F), the recursive least squares estimation technique produces much better results than the algebraic estimation technique. This is because it is less susceptible to poor measurements, given it uses more data to undertake the estimation.
- The recursive least squares estimation technique produces better results despite the magnitude of the power deviations being lower.

The size of the error for the resistance may be a point of concern – but due to the X/R ratio of 10, the resistance is actually very small, making it more difficult to identify. This observation is particularly important when comparing these results to those obtained in [10], where the X/R ratio of 0.75 allowed for better resistance estimations. Therefore, should this method be used at transmission level X/R ratios, one should be aware that the inductance estimations are much better than the resistance estimations.

The final observation is that utilising active power and voltage magnitude deviations due to the converter operating with a weak grid specific outer loop (instead of active and reactive power) also produces valid impedance estimations.

6 Conclusion

A thorough series of tests aimed at assessing the robustness of two impedance estimation techniques is presented in this paper, where the optimum power and voltage magnitude deviations are determined for both the algebraic and the recursive least squares estimation techniques. The two estimation techniques are also compared against one another in various grid layouts and noise conditions, and it has been demonstrated that the recursive least squares estimation technique produces the most consistent and accurate results, despite introducing smaller changes to the power and voltage magnitude set-points. The optimum U_{seq} multiplier is 3.3 and 4.15. It has been noted that transmission level X/R ratios generate poor resistance estimation.

7 Acknowledgements

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8 Data Statement

The data that support the findings of this study are openly available at the University of Strathclyde's PURE portal at https://doi.org/10.15129/4a7c2b95-42d0-4d53-bd4e-fc98f1ac2cf0.

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Table 6 Results for Test E: Recursive least squares estimation technique, complex grid, no noise simulated

P dev (%)	U dev (%)	SCR 5.8 L_{err} (%)	SCR 5.8 R_{err} (%)	SCR 4.4 L_{err} (%)	SCR 4.4 R_{err} (%)	SCR 2.3 L_{err} (%)	SCR 2.3 R_{err} (%)
P_{seq}	U_{seq} ·3.3	-1.0	56.9	-1.5	41.1	-1.3	1.7
P_{seq}	U_{seq} ·4.15	-1.0	54.1	-1.4	37.7	-1.2	-7.2
P_{seq}	U_{seq} ·5	-1.0	52.2	-1.4	35.2	-1.1	-13.5

Table 7 Results for Test F: Recursive least squares estimation technique, RL grid, noise simulated

P dev (%)	U dev (%)	SCR 7 L_{err} (%)	SCR 7 R_{err} (%)	SCR 5 L_{err} (%)	SCR 5 R_{err} (%)	SCR 3 L_{err} (%)	SCR 3 R_{err} (%)	SCR 1.5 L_{err} (%)	SCR 1.5 R_{err} (%)
P_{seq}	U_{seq} ·3.3	-14.0	114.0	3.4	100.8	-10.8	43.4	-0.2	-2.9
P_{seq}	U_{seq} ·4.15	0.8	46.9	0.6	-36.1	-2.4	-3.0	1.1	-99.4
P_{seq}	U_{seq} ·5	-4.8	63.0	-1.9	116.9	-1.8	-10.1	-7.1	-55.2

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