A Real-Time EMT Benchmark Model for Power Electronics Defined Power System Analysis

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***Abstract*—The increasing share of inverter-based resources (IBRs) and the planned retirement of coal-fired generation with its associated synchronous units are transforming the dynamics of modern power systems. To enable detailed analysis under these evolving conditions, this work presents the development for real-time simulation of an updated IEEE Australian 14-generator benchmark model, the 13-Gen-REZ, that reflects recent generation retirements and the inclusion of renewable energy zones (REZs). The redevelopment for real-time (RT) simulations expands previous models for EMT-type studies, allowing detailed analysis of power electronics defined power systems under varying operating conditions and with the option for hardware-in-the-loop testing and validation. The model preserves the essential structural and dynamic characteristics of a large interconnected power system allowing comparisons with previous model versions. It incorporates changes in the network topology with the addition of REZs, generator retirements and different IBR control strategies. It serves as a platform for analysing grid-following and grid-forming control strategies at network level, fault current characteristics with current-limited IBRs, interactions with protection systems and stability phenomena associated with high IBR penetration. The presented results offer validation against offline EMT and phasor-based simulations.**

***Index Terms*—Benchmark model, electromagnetic transient (EMT) simulation, real-time (RT) simulation.**

I. INTRODUCTION

As power systems transition towards inverter-based resources (IBRs), current models must also be adapted and updated to reflect the characteristics of such transition. More specifically, the fast phenomena caused by renewables drastically change system behaviour compared to traditional systems dominated by slow, synchronous generation. The ability to investigate effects related to faster phenomena is becoming increasingly critical for maintaining stability and secure operation during normal operation and transient events [1]. Such phenomena have been observed both in Australia and globally [2], [3]. Notably, the black system event that affected South Australia (SA) in 2016 where 48% of the electricity supply from wind farms were lost due to protection settings not configured to handle multiple faults in quick succession [4]. This resulted in a rapid rise of power flow through the Heywoood Interconnector, activating the protection system, separating SA from the rest of the grid and causing the frequency to fall rapidly. This tripped the remaining generation, causing a state wide blackout. Such events highlight the need for accurate models capable of capturing complex dynamics so that system instability can be identified and mitigated.

Compared to traditional phasor-based models, control and transient responses from IBRs are significantly faster than the frequency of the system [5]. Therefore, observation of the effects of such phenomena requires detailed EMT modelling of all elements, and thus, substantial additional computational resources. For example, the offline EMT model that forms the basis of the real-time (RT) model developed in this work requires approximately 1 hr to complete 50 s of simulation [6].

Real-time simulations offer the benefits of both quicker simulation times with the increased accuracy of EMT modelling. Furthermore, they allow for the testing of real hardware and control algorithms against a simulated network, providing a controlled environment for testing operational changes, evaluating system stability and assessing the impact of new technologies before they are implemented in the real world. This work outlines the methodology behind converting the reduced 2024 Australian National Electricity Market (NEM) PSCAD model into a RT model, the 2024 13-Gen-REZ benchmark model.

II. EXPANSION OF THE IEEE SIMPLIFIED AUSTRALIAN 14-GENERATOR BENCHMARK MODEL

A. Background

As part of the Australian Research in Power Systems Transition (AR-PST) program, forward-looking models of the NEM were developed to support analysis of operational and stability challenges under high levels of IBRs. These reduced PSCAD models capture projected generation mixes, demand profiles, and network configurations across key forecast years between 2024 and 2034, suitable for large-scale dynamic studies [7].

The aforementioned PSCAD models are derived from the IEEE Simplified 14-Generator Model (14-Gen) [8], a longitudinal benchmark model, loosely based on the NEM, but without accurately representing specific aspects of the network. The primary purpose of the original model was to serve as a test-system for small-signal analysis and power system stabiliser (PSS)/controller design in a multi-machine network[1]. The new RT model is revised in accordance with the topology and generation changes outlined in AEMO's latest Integrated System Plan (ISP [10]) and the inclusion of additional IBRs as described in [6].

[1]Interested readers may refer to [9] for a larger scale, general use, real-time synthetic model of the NEM, the S-NEM2300.

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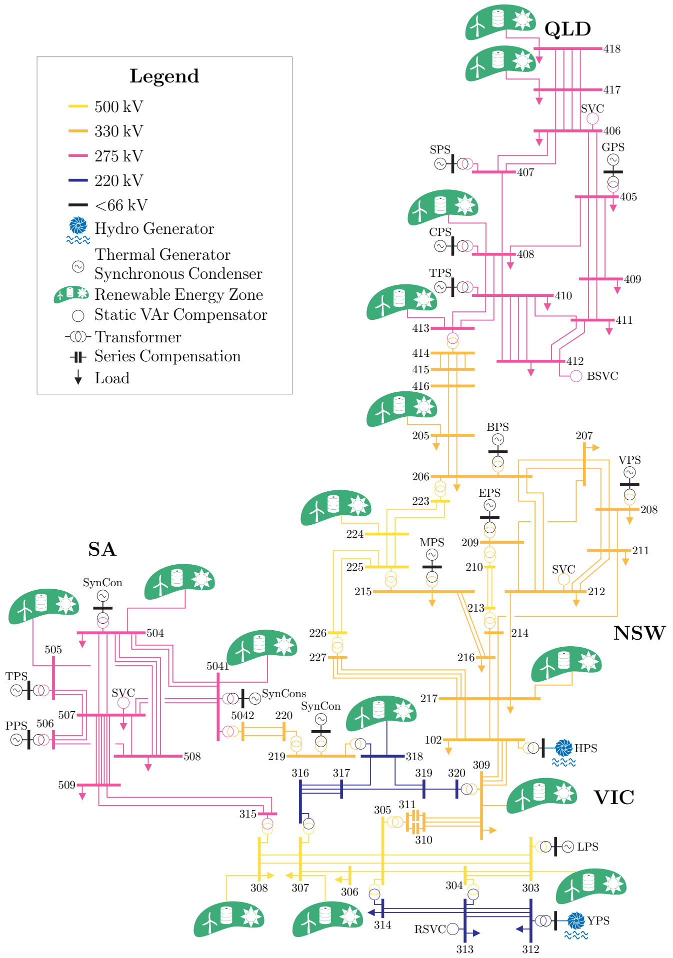

Fig. 1. Schematic diagram of the updated 13-Gen benchmark model, the 13-Gen-REZ, including the location of new renewable energy zones, transmission lines and interconnectors between states.

All previous real-time models and the currently under development, 13-Gen-REZ model, are openly available in http://bit.ly/RTBenchmark_14-Gen[2].

B. *Expansion of Renewable Generation*

Network expansion planning in Australia is increasingly guided by the renewable energy zone (REZ) framework, which coordinates transmission development with the staged deployment of renewable generation in resource-rich regions to optimise system efficiency and investment outcomes. A REZ refers to a geographically defined area identified as optimal for large-scale renewable energy generation, including energy storage, and network connection due to its high-quality resources and existing or planned transmission infrastructure.

Expansion of the original 14-Gen with IBRs (i.e., solar, wind and BESS) [11] included standalone units and at relatively small proportion to existing synchronous generation, consistent with the generation mix of the NEM during the 2017–2018 period. To be included in this reduced model, a REZ must be greater than 1 GW. As the generation type and

[2]Appropriate simulator resources are required to run the models.

TABLE I
NEWLY INTRODUCED RENEWABLE ENERGY ZONES (REZS)

Bus	Approximate Location	Area	MVA
418	Ross	QLD	4000
417	Strathmore	QLD	1000
408	Callide	QLD	4000
413	Braemar	QLD	2000
205	Armidale	NSW	4000
224	Wollar	NSW	4000
217	Yass	NSW	2000
309	Dederang	VIC	2000
303	Loy Yang	VIC	4000
318	Buronga	VIC	2000
307	Moorabool	VIC	2000
308	Heywood	VIC/SA	2000
5041	Roberstown	SA	2000
504	Davenport	SA	4000
505	Torrens Island	SA	2000

percentages are unknown, REZ capacity has been equally split between wind, PV generation and BESS. The schematic of the 13-Gen-REZ model is shown in Fig 1 while a summary of all new REZs is given in Table I.

III. DEVELOPMENT OF THE 13-GEN-REZ REAL-TIME MODEL

Transmission lines and network buses were directly converted from the PSCAD model through the built-in conversion tool. All remaining network elements were either created or adapted from previous generic models.

A. *Synchronous Machine and SVC Modelling*

1) Synchronous Generators (SGs): The reference PSCAD model disaggregated the synchronous machines derived from the 14-Gen model to allow for the impact of online synchronous machines to be studied. However, given the current size of the model and the negligible impact of the disaggregated set, the RT equivalent of the 14-Gen generator models, including stabilisers governors and exciters, developed in [11] were adopted for this manuscript. These machines were configured with an inertia constant to improve the accuracy of the network's dynamic response.

2) Exciters: Compared to the 14-Gen model, the exciters in the PSCAD model utilised the new ST1C and AC1C models rather than the earlier ST1A and AC1A versions. The newer versions allow for the added capability to connect under-excitation limiters (UEL) and over-excitation limiters (OEL) but their dynamic behaviour remains unchanged. In this work, the ST1A and AC1A models were retained, as RT equivalents of the ST1C and AC1C are not currently available, and the expected impact on system behaviour was negligible.

3) Synchronous Condensers (SynCons): Synchronous condensers were developed by adapting similarly sized synchronous machines from [11]. Consistent with the reference approach, both the governor and stabilisers were removed.

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4) Static VAr Compensators (SVC): The reference model scales the built-in PSCAD SVC example to match the data provided with the 14-Gen model. RT equivalents of these SVCs were previously developed in [11]. The same models have been adopted from the present work.

B. Real-Time Modelling of REZs

Previously developed generic RT models of battery energy storage systems (BESSs), PV and wind [11] were used in place of the hybrid PV-BESS [12] and generic type IV wind turbine models used in the 2024 PSCAD model[3]. As these models operate at switching frequencies faster than the main RT simulation time-step (50 µs), each required a dedicated small-time step interface, which results in significant computational requirements, beyond the available capacity of our simulator, should all three generation types per REZ be included. Consequently, each REZ was represented by a single RT model of a BESS, allowing for bidirectional power flows (if required) and independent control of active and reactive power. Furthermore, the BESS models can be enabled for droop control functionality, simulating FCAS-style frequency response currently operating in the NEM.

It should also be noted that while the present single BESS model captures and can replicate the aggregate dynamic behaviour of each REZ, detailed assessments of the internal stability of individual REZs, including verification that no adverse interactions occur among multiple converters, were not undertaken and remain outside the scope of this study. Additionally, some REZs may include SynCons to provide local voltage and inertia support, but these devices were not represented in either the reference or the RT models.

C. Computational Requirements

Due to the scale and detail of the network (summary of components shown in Table II), the developed 13-Gen-REZ model requires 10 PB5-based RTDS racks, each equipped with 6 PB5 processors. 15 PB5s are allocated to the REZs, running at ≈2.55 µs to allow the accurate simulation of high-frequency switching circuits, while 25 PB5s running at 50 µs for the rest of the components and the network solution. The remaining 20 PB5s are not utilised to allow network expansions such as, more detailed REZs (e.g., wind farms which require 1.5 PB5s), transmission system upgrades, and the 2034 version of the model. Preliminary estimates indicate that the 2034 version of the model will require all idle PB5 cards and 36 additional ones (a total of sixteen fully equipped PB5-based racks).

IV. Real-time Simulations and Results

A. Steady State - Loadflow

A fast decoupled Newton-Raphson calculation, with a maximum MVA error of 0.001 MVA, is used to solve the loadflow of the system. Table III shows the obtained results and a comparison against its PSCAD counterpart. As it can be seen, the loadflows present small differences. In terms of active power, there is a 5.19 MW difference occurring at the slack bus, resulting in a total difference of 0.06%. Reactive power has a slightly bigger difference of 5.39%. This difference is expected as the PSCAD model uses PSS/E data to initailise the loadflow, which uses constant P for the loads while RSCAD uses constant Z for loads, accounting for differences seen in the results. The average mismatch between bus magnitude and angle is 0.017 p.u. and 0.61°, with a maximum mismatch of 0.045 p.u. at bus 206 and 1.32° at bus 508. All voltages are within 5% each other, indicating good consistency between the two models. This close agreement validates the appropriate model development, parameter translation and the validity of the final real-time model.

TABLE II
SUMMARY OF NETWORK COMPONENTS IN THE 13-GEN-REZ RT MODEL

Buses	61
Synchronous generators (SGs)	13
Renewable energy zones (REZs)	15
Synchronous condensers (SynCons)	4
Static VAr compensators (SVCs)	5
Transmission lines	123
Transformers	31
Dynamic loads	30

TABLE III
RESULTS OF LOADFLOW CALCULATIONS AND COMPARISON BETWEEN THE ORIGINAL (PSCAD) AND THE REAL-TIME (RSCAD) MODEL

Bus	Type	PSCAD		RSCAD		△MW	△MVAr
		MW	MVAr	MW	MVAr		
102	SG	5.89	29.72	11.07	299.80	-5.19	-270.08
205	REZ	200.00	-94.21	200.00	-29.86	0.00	-64.35
206	SG	600.00	-49.51	600.00	-273.72	0.00	224.21
208	SG	200.00	-92.42	200.00	-194.29	0.00	101.87
209	SG	400.00	-308.76	400.00	-239.87	0.00	-68.89
212	SVC	0.00	0.00	0.00	28.21	0.00	-28.21
215	SG	600.00	81.09	600.00	-225.43	0.00	306.52
217	REZ	414.82	-779.77	414.82	-882.75	0.00	102.98
219	SynCon	0.00	19.10	0.00	-67.93	0.00	87.03
224	REZ	155.56	-869.30	155.56	-506.60	0.00	-362.70
303	SG	700.00	201.92	700.00	8.83	0.00	193.09
303	REZ	233.33	-372.80	233.33	-388.00	0.00	15.19
307	REZ	233.33	-902.41	233.33	-772.58	0.00	-129.83
308	REZ	233.33	-275.34	233.33	-337.49	0.00	62.15
309	REZ	233.33	-455.67	233.33	-458.79	0.00	3.12
312	SG	400.00	-51.18	400.00	-77.68	0.00	26.50
313	SVC	0.00	16.64	0.00	55.63	0.00	-38.99
318	REZ	233.33	-94.00	233.33	-93.06	0.00	-0.94
405	SG	300.00	-87.55	300.00	11.21	0.00	-98.76
406	SVC	0.00	0.00	0.00	-0.23	0.00	0.23
407	SG	200.00	-33.03	200.00	-62.03	0.00	29.01
408	SG	200.00	13.13	200.00	3.61	0.00	9.52
408	REZ	544.45	-207.82	544.45	-275.46	0.00	67.64
410	SG	400.00	14.85	400.00	-183.66	0.00	198.5
412	SVC	0.00	-320.68	0.00	-16.32	0.00	-304.35
413	REZ	466.67	-333.15	466.67	-370.63	0.00	37.48
417	REZ	155.56	-230.94	155.56	-276.83	0.00	45.89
418	REZ	207.41	-85.90	207.41	-82.05	0.00	-3.85
504	SynCon	0.00	0.00	0.00	0.00	0.00	0.00
504	REZ	233.33	-64.59	233.33	-183.23	0.00	118.64
505	SG	100.00	-60.93	100.00	255.61	0.00	-316.54
505	REZ	0.00	50.92	0.00	-386.27	0.00	437.19
506	SG	300.00	73.91	300.00	108.39	0.00	-34.48
507	SVC	0.00	-161.78	0.00	24.31	0.00	-186.09
5041	SynCon	0.00	-16.67	0.00	0.01	0.00	-16.66
5041	SynCon	0.00	-16.67	0.00	0.01	0.00	-16.66
5041	REZ	129.63	-10.24	129.63	-179.78	0.00	169.55
Totals		8079.97	-5474.03	8085.15	-5768.90	0.06%	5.39%

B. Dynamic Real-Time EMT Simulation - Faults

To illustrate the real-time and dynamic behaviour of the system, two-phase and three-phase to ground faults are applied

[3]The shared PSCAD EMT model of [6] included placeholders at each REZ and requires additional third party models for simulation.

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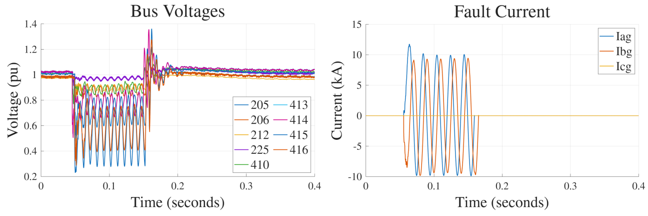

Fig. 2. Two-Phase Fault on Bus 205, (a) Bus Voltages, and (b) Fault Currents.

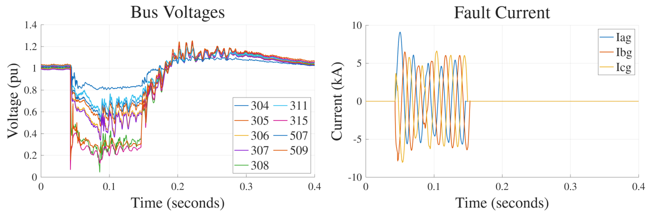

Fig. 3. Three-Phase Fault on Bus 315, (a) Bus Voltages, and (b) Fault Currents.

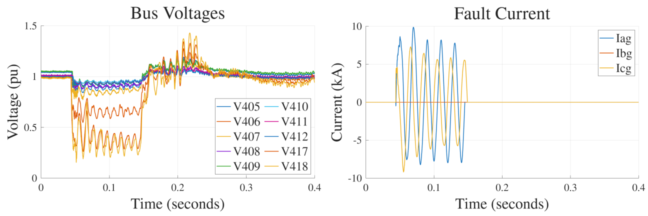

Fig. 4. Two-Phase Fault on Bus 417, (a) Bus Voltages, and (b) Fault Currents.

to different buses in the system. As it can be seen from the results (Fig. 2 to Fig. 4), the system remains stable in all cases and faults are well damped, as bus voltages (RMS) remain within a $\pm 10\%$ from their original pre-fault values. Also, to illustrate the EMT capabilities of the model, fault phase currents are provided.

C. System Strength Evolution

System strength is a nodal indicator of a power system's ability to maintain and control voltage at any given location under both steady-state conditions and during disturbances. It indicates how robust a grid is and it is usually measured with the short-circuit capacity (SSC). As power systems transition to higher IBR proportions, it is essential to provide minimum system strength to maintain a stable and secure operation.

Three-phase faults, with a duration of 100 ms, are independently applied to buses in the system to evaluate how system strength has evolved in this model (13-Gen-REZ) with respect to the original 14-Gen model. Table IV summarises the results when considering all synchronous machines connected (main source of fault current), and it is possible to observe that, overall, system strength is maintained between both models. Even though the new model contains less SGs, the fault contribution and thus, the SCC, remains approximately the same due to the addition of SynCons and new branch connections. This is most evident in the SA subnetwork, where one SG was removed, but three SynCons where added and both intra- and inter-area connections were included.

TABLE IV
SYSTEM STRENGTH EVOLUTION

Bus	Voltage [kV]	SSC [GVA]		Variation [%]
		13-Gen-REZ	14-Gen	
211	330	4.06	4.09	-0.8
305	500	5.89	6.20	-5.0
409	275	1.95	1.86	4.4
507	275	2.63	2.31	13.9

D. Discussion

To improve the stability of the dynamic simulations three 300 MVAr, one 200 MVAr and one 100 MVAr shunts were added to the system, mirroring placement to the PSCAD model (but different to the provided loadflow model). To reconcile these discrepancies, REZ P/Q setpoints were adjusted for dynamic simulations. In the reference model, the generic PSCAD model of SVCs were used with the sizing of each device altered to match the original 14-Gen model. This model does not have an exact equivalent in the RTDS library. While parameters were aligned were possible, differences in the modelling framework contribute to variations of reactive power observed in the simulation results. Similarly, there was a difference in saturation parameters for transformers, with RSCAD including a default value for Eddy current loss of 0.05%. This variable was not present in the PSCAD model.

Dynamic models of loads were used instead of constant values, allowing for dynamic adjustment of loads during disturbances. The P and Q setpoints are adjusted to keep the system frequency within ± 2 Hz. In addition, an exponential coefficient calculation block is used to calculate the setpoints for P and Q by reading the real and reactive power orders and calculating the corresponding set points based on:

$$P_{set} = P^* \cdot \left(\frac{V}{V_o}\right)^{K_{pv}} \cdot [1.0 + K_{pf} \cdot (f - f_0)] \quad \text{and}$$

$$Q_{set} = Q^* \cdot \left(\frac{V}{V_o}\right)^{K_{qv}} \cdot [1.0 + K_{qf} \cdot (f - f_0)].$$

For the results in this report, K_{pv}, K_{qv}, K_{pf} and K_{qf} were set to 0.

V. MODEL LIMITATIONS & FUTURE WORK

The reduced model simplifies loads into Thevenin equivalents, while this model aims to increase the accuracy of the dynamic response using dynamic loads, there is still non-linearities that will not be captured. Furthermore, the simplification of network topology and transmission line representation reduces the accuracy of surge behaviour and impedance discontinuities.

Future work includes the expansion of the current model to project the 2034 system. This includes additional transmission lines, removal of 11 synchronous generators to be replaced by SynCons and the addition of 6 more REZs. Models of REZs will further be expanded to include grid-forming capabilities allowing for simulation of different control modes.

Further analysis on steady state and dynamic response validation will be conducted to benchmark the 13-Gen REZ

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against the existing PSCAD model. This will include a 8 GW operational demand case and a 36 GW operational demand case to simulate a light and heavy load on the network respectively. Dynamic responses will be simulated for benchmarking against the reference PSCAD model. Furthermore, the dynamic load constants will also be varied to assess sensitivity and the effects of system reduction on the network's dynamic response.

VI. Conclusion

An openly available, real-time Australian 13-generator benchmark model provides an updated platform that reflects recent network developments, synchronous generator retirements, and the introduction of REZs. The model also enables direct comparison with earlier synchronous-only, weakly interconnected benchmark models.

Its compatibility with hardware-in-the-loop (HiL) testing enables the development and validation of grid-following and grid-forming control strategies, as well as detailed assessment of stability, protection interactions, and power-electronics-defined dynamics. In addition to introducing the real-time model, this paper validates its steady-state performance against offline EMT and phasor-domain simulations and establishes a flexible foundation for analysing power systems with high proportions of IBRs, providing clear guidelines for future work in the area.

Appendix

Table V presents a bus-by-bus comparison of the voltages obtained from the PSCAD EMT simulation model and the RSCAD/RTDS RT simulation model. The results show that all voltage values are within 5% of each other, indicating excellent consistency between the two models. This close agreement validates the appropriate model development, parameter translation and the validity of the final real-time model.

Acknowledgement

This work was supported by the ARC Future Fellowships scheme under Grant ARC FT240100038. The authors acknowledge the Commonwealth Scientific and Industrial Research Organisation and the authors of [6] for providing models developed as part of AR-PST Stage 4 Topic 6.

TABLE V
Comparison of Bus Voltages and Angles

Bus	V (kV)	PSCAD		RSCAD		Δ	
		PU	Angle	PU	Angle	PU	Angle
102	330	1.0296	-0.2246	1.0396	-0.0516	0.0100	0.1730
205	330	1.0200	6.2984	1.0000	6.8647	0.0200	0.5663
206	330	1.0579	2.7193	1.0133	3.2755	0.0446	0.5562
207	330	1.0498	-0.5332	1.0128	-0.2597	0.0370	0.2735
208	330	1.0494	-1.2430	1.0102	-1.0016	0.0392	0.2414
209	330	1.0461	-0.0317	1.0140	0.2459	0.0320	0.2776
210	500	1.0595	-0.4533	1.0276	-0.1875	0.0319	0.2658
211	330	1.0513	-2.6097	1.0178	-2.4987	0.0335	0.1110
212	330	1.0513	-2.6144	1.0208	-2.5447	0.0305	0.0697
213	500	1.0616	-0.9059	1.0302	-0.6524	0.0314	0.2535
214	330	1.0530	-1.3237	1.0223	-1.0810	0.0307	0.2427
215	330	1.0430	3.2145	1.0094	3.7691	0.0336	0.5546
216	330	1.0467	-1.3713	1.0164	-1.1127	0.0303	0.2586
217	330	1.0200	0.2228	1.0000	0.6071	0.0200	0.3843
219	330	1.0022	14.3978	1.0027	13.3563	0.0005	1.0415
220	330	1.0011	13.9598	1.0105	12.9212	0.0094	1.0386
223	500	1.0581	2.7895	1.0170	3.3452	0.0411	0.5557
224	500	1.0000	3.6435	1.0001	4.1269	0.0001	0.4834
225	500	1.0358	3.0229	1.0162	3.5665	0.0196	0.5436
226	500	1.0443	2.1003	1.0243	2.5969	0.0200	0.4966
227	330	1.0422	1.5776	1.0222	2.0433	0.0200	0.4657
303	500	1.0200	0.8853	1.0000	0.1451	0.0200	0.7402
304	500	1.0184	-1.8088	1.0074	-2.6580	0.0110	0.8492
305	500	1.0156	-1.6950	1.0048	-2.5395	0.0108	0.8445
306	500	1.0116	-1.8275	1.0014	-2.6748	0.0102	0.8473
307	500	1.0100	-1.7124	1.0001	-2.5576	0.0099	0.8452
308	500	1.0200	-1.6277	1.0000	-2.4671	0.0200	0.8394
309	330	1.0000	0.5539	1.0000	0.7517	0.0000	0.1978
310	330	1.0141	-2.0199	1.0031	-2.8604	0.0110	0.8405
311	330	1.0196	-0.8956	1.0091	-1.7502	0.0105	0.8546
312	220	1.0209	-2.3473	1.0154	-3.2069	0.0055	0.8596
313	220	1.0200	-5.2786	1.0186	-6.1817	0.0014	0.9031
314	220	1.0191	-5.2802	1.0149	-6.1708	0.0042	0.8906
315	275	1.0310	-1.4314	1.0120	-2.2931	0.0190	0.8617
316	220	1.0160	-0.6224	1.0067	-1.4118	0.0093	0.7894
317	220	1.0239	0.4379	1.0159	-0.2690	0.0080	0.7069
318	220	1.0000	15.8229	1.0000	14.8073	0.0000	1.0156
319	220	1.0295	2.6087	1.0255	2.1788	0.0040	0.4299
320	220	1.0042	0.8132	1.0040	0.9312	0.0002	0.1180
405	275	1.0446	4.3762	1.0494	4.5838	0.0048	0.2076
406	275	1.0475	6.7940	1.0335	7.0888	0.0140	0.2948
407	275	1.0330	11.7331	1.0111	12.2194	0.0219	0.4863
408	275	1.0200	12.9566	1.0000	13.4610	0.0200	0.5044
409	275	1.0521	-1.9251	1.0640	-1.5672	0.0119	0.3579
410	275	1.0197	1.7942	1.0119	2.1997	0.0078	0.4055
411	275	1.0113	-4.1580	1.0282	-3.7592	0.0169	0.3988
412	275	1.0000	-3.3299	1.0212	-2.9757	0.0212	0.3542
413	275	1.0200	7.5630	1.0000	8.1774	0.0200	0.6144
414	330	1.0273	7.4983	1.0072	8.1100	0.0201	0.6117
415	330	1.0393	7.2959	1.0189	7.9018	0.0204	0.6059
416	330	1.0472	6.7231	1.0266	7.3101	0.0206	0.5870
417	275	1.0300	8.0952	1.0000	8.4587	0.0300	0.3635
418	275	1.0300	8.9518	1.0000	9.3603	0.0300	0.4085
504	275	1.0300	9.2814	1.0000	8.6548	0.0300	0.6266
505	275	1.0200	7.6055	1.0001	6.3586	0.0199	1.2469
506	275	1.0253	8.2955	1.0158	7.0017	0.0095	1.2938
507	275	1.0200	7.2384	1.0110	5.9393	0.0090	1.2991
508	275	1.0182	7.2686	0.9981	5.9537	0.0201	1.3149
509	275	1.0473	-1.1955	1.0302	-2.1157	0.0171	0.9202
5041	275	1.0200	10.4647	1.0000	9.5746	0.0200	0.8901
5042	330	1.0134	10.8867	1.0069	10.0097	0.0065	0.8770

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